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of Visual-Motion Time Delays
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Hampton, Virginia



National Aeronautics
and Space Administration

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SUMMARY

An experimental study has been made to determine the effect of time delay in the visual and motion cues in a flight simulator on pilot performance in tracking a target aircraft that was oscillating sinusoidally in altitude only. An audio side task was used to assure that the subject was fully occupied at all times. The results of the study indicate that, within the test grid employed, about the same acceptable time delay (250 msec) was obtained for a single aircraft (fighter type) by each of two subjects for both fixed-base and motion-base conditions. Acceptable time delay is defined as the largest amount of delay that can be inserted simultaneously into the visual and motion cues before performance degradation occurs. A statistical analysis of the data was made to establish this value of time delay. Use of the audio side task provided quantitative data that documented the subject's work level.

INTRODUCTION

In the ideal situation, simulators should provide the subject with visual and motion cues like those that would be experienced in the real vehicle. Exact duplication of flight cues, however, is impossible. It is important, therefore, to determine how much degradation in simulator cues can exist before the subject's performance is affected. One factor impacting this problem is the presence of time delays in the simulation. Time delays can arise, for example, from such sources as the sampling rates used in the digital computing system and the time required to produce computer generated images. A number of experimental studies have been made to try to establish the amount of time delay that can be tolerated in the visual and motion cues given to the subject of a flight simulator. A summary report containing an extensive bibliography of time delay studies is given in reference 1. Of the available studies, references 2 and 3 are of particular interest since the present study is an extension of that work.

The purpose of the present study was to reexamine the effect of time delay in the visual and motion cues of a flight simulator on pilot performance in a visual tracking task with a different side task. A side task was employed in this and the previous studies to assure the pilot was fully occupied at all times. The side task of references 2 and 3 was a self-pacing tapping task that forced a visual interruption in primary task concentration. Since there were few operating instructions, each subject implemented the side task differently. Also, because of the visual interruption, large variations were obtained in each subject's primary task performance. The side task selected for the present study was different from that of references 2 and 3 and was the only change in the experimental setup. The present study used an audio side task whose difficulty was adjusted by the experimenters. This side task eliminated sharing of the subject's visual channel between primary and side tasks as was done in references 2 and 3. In the current study a single aircraft (fighter type) was used to perform a target tracking task by each of two subjects.

Results were obtained for fixed-base and single motion-base condition (best motion of ref. 3) for a range of added time delay from 0 to 1/2 sec.

A brief comparison of selected results using the audio task and the tapping task is included. A comparison of the effect on pilot performance of several side tasks including the tapping and audio tasks is given in reference 4.

SYMBOLS

a	acceleration caused by aerodynamic forces, m/sec ²
B	audio task tracking error (tone voltage), volts or Hz (scale factor is 460 Hz/volt)
F	statistical quantity associated with F distribution
F _y	side force, N
g	gravitational acceleration, 1g = 9.8 m/sec ²
I	moment of inertia, kg-m ²
K _n	gains used in motion-base drive equations (n = 0 to 18)
K _*	pilot gain
L	lift force, N
L ₀	$= \frac{\text{Trim lift}}{mV_{x,0}}, \text{ per sec}$
L _p	$= \frac{1}{I_X} \frac{\partial M_X}{\partial p}, \text{ per sec}$
L _r	$= \frac{1}{I_X} \frac{\partial M_X}{\partial r}, \text{ per sec}$
L _α	$= \frac{1}{mV_{x,0}} \frac{\partial L}{\partial \alpha}, \text{ per sec-rad}$
L _β	$= \frac{1}{I_X} \frac{\partial M_X}{\partial \beta}, \text{ per sec}^2$
L _{δ_a}	$= \frac{1}{I_X} \frac{\partial M_X}{\partial \delta_a}, \text{ per sec}^2$

l_j, m_j, n_j direction cosines ($j = 1, 2, 3$)

$$M_q = \frac{1}{I_Y} \frac{\partial M_Y}{\partial q}, \text{ per sec}$$

M_X rolling moment, N-m

M_Y pitching moment, N-m

M_Z yawing moment, N-m

$$M_{\alpha} = \frac{1}{I_Y} \frac{\partial M_Y}{\partial \alpha}, \text{ per sec}^2$$

$$M_{\delta_e} = \frac{1}{I_Y} \frac{\partial M_Y}{\partial \delta_e}, \text{ per sec}^2$$

m aircraft mass, kg

$$N_p = \frac{1}{I_Z} \frac{\partial M_Z}{\partial p}, \text{ per sec}$$

$$N_r = \frac{1}{I_Z} \frac{\partial M_Z}{\partial r}, \text{ per sec}$$

$$N_{\beta} = \frac{1}{I_Z} \frac{\partial M_Z}{\partial \beta}, \text{ per sec}^2$$

$$N_{\delta_a} = \frac{1}{I_Z} \frac{\partial M_Z}{\partial \delta_a}, \text{ per sec}^2$$

$$N_{\delta_r} = \frac{1}{I_Z} \frac{\partial M_Z}{\partial \delta_r}, \text{ per sec}^2$$

p angular rate around aircraft longitudinal body axis, rad/sec

p_K roll motion drive signal before compensation, rad/sec

q angular rate around aircraft lateral body axis, rad/sec

r angular rate around aircraft normal body axis, rad/sec

s Laplace operator

T_S	audio task first-order divergence time constant, sec
$t()$	statistical quantity of "t"-test of student's t distribution; parentheses designate particular factor considered
u, v, w	aircraft velocities along longitudinal, lateral, and normal body axes, respectively, m/sec
V_x, V_y, V_z	components of aircraft velocity relative to inertial space, m/sec
Y_β	$= \frac{1}{mV_{x,0}} \frac{\partial F_y}{\partial \beta}, \text{ per sec-rad}$
y_c, z_c	lateral and vertical drive commands, respectively, for motion base, m
y_k	lateral motion drive signal before compensation, m
z_k	vertical motion drive signal before compensation, m
α	change in angle of attack from trim, rad
β	sideslip angle, rad
δ_a	aileron deflection, rad
δ_e	elevator deflection, rad
δ_r	rudder deflection, rad
δ_s	audio task thumb-wheel deflection, volts (scale factor is 0.4 rad/volt)
ϵ_h	horizontal (lateral) tracking error, m
ϵ_v	vertical tracking error, m
$\epsilon_v + \epsilon_h$	total tracking error, m
η	elevation line-of-sight angle, rad
θ_c, φ_c	pitch and roll drive commands for motion base, rad
λ	audio task instability setting, $1/T_S$, sec^{-1}
ξ	azimuth line-of-sight angle, rad
$\bar{\sigma}$	unbiased estimate of standard deviation
τ	units of added time delay in visual and motion cues (each unit equals 31.25 msec)

τ_e pilot effective time delay, sec

τ_m units of added time delay in motion cues (each unit equals 31.25 msec)

τ_v units of added time delay in visual-scene display (each unit equals 31.25 msec)

ψ, θ, φ Euler angles, deg or rad

ω_{δ_s} audio task thumb-wheel input frequency, Hz

Subscripts:

o initial condition

vco voltage controlled oscillator

X,Y,Z aircraft body axes

Abbreviations:

ANOV analysis of variance

DAC digital-to-analog converter

d.o.f. degrees of freedom

L.O.S. magnitude of radial line-of-sight angle of target from tracker, rad

VMS visual-motion simulator

rms root mean square

A dot over a quantity indicates a derivative with respect to time. The notation rms () indicates rms value of the variable in parentheses for a single run. A bar over a symbol indicates the arithmetic mean of rms () values for all runs having identical test conditions.

TEST HYPOTHESIS

The strategy used in this paper is the same as that of reference 2. Two tasks, a primary task and a side task, are combined so that in performing the total task, the subject is working at his full capacity. This situation is established for the zero time delay condition. The zero time delay condition considered in this paper is that which exists for the simulator in its normal operating mode. Additional time delays are then inserted into the visual and motion cues given to the subject. If the presence of these additional time delays does not impact the combined task, pilot performance should not change. If, however, the presence of these time delays increases the task difficulty, a degradation in performance would occur. Acceptable time delay is defined, therefore, as the largest additional time delay that can be inserted into the

visual and motion cues before a performance degradation occurs. A statistical analysis of the data is performed to establish performance degradation at the 5-percent level of significance.

DESCRIPTION OF APPARATUS

The tests were performed in the Langley visual-motion simulator (VMS) which is a hydraulically operated, six-legged synergistic motion base. (See fig. 1.) Six computed leg positions are used to drive the motion base. The computed actuator extensions are passed from the computer to the motion base through digital-to-analog converters (DAC) every 31.25 msec. To eliminate the stair-stepping in this output and provide smooth continuous signals for driving the motion base, the DAC outputs are passed through notch filters on the hardware. Filter characteristics are given in reference 5, and the transformations used to compute the leg extensions are given in reference 6. References 5 and 7 give the performance limits of the VMS. For the present study, the VMS was used both as a fixed-base and as a motion-base simulator.

The pilot's compartment is representative of a two-man cockpit (fig. 2). Although the panel instruments were illuminated, they were not operational and were not used by the pilot subjects. Visual cues (target aircraft) were generated by a small model and closed-circuit television. The model was mounted in a two-axis gimbal support and was rotated in pitch and yaw in response to the relative motion of the tracker and target aircraft so that the subject saw the proper aspect of the target. Target aircraft roll was accomplished electronically. Elevation and azimuth changes of the target aircraft in the display were obtained by repositioning the television raster electronically. The repositioning was accomplished by using scaled voltages to represent angles of deflection in elevation and azimuth. This technique eliminated unwanted delays in visual-scene display; such delays occur when electromechanical systems (involving mirrors, gears, and electric motors) are used to obtain elevation and azimuth positions. The image was displayed by use of a television screen (fig. 3) with an infinity optics mirror. The horizon was also projected on the screen. A reticle (two crossed lines) was projected on the center of the screen to represent sights on the aircraft flown by the subject.

The subject maneuvered his aircraft by using a two-axis finger-tip pencil controller of the force-stick type; this device controlled rotations about the aircraft pitch and roll body axes. Force-stick characteristics are given in figure 4. The controller is shown in the photograph of figure 2. The equations of motion of the pursuing (tracker) aircraft are given in appendix A. All equations of the simulation, except those for the audio task, were solved on a digital computer. The digital outputs were then converted to analog signals to drive the visual-scene and motion generation equipment. The Langley Research Center hardware for computer signal processing from analog to digital and back to analog can be represented mathematically as a prefilter, a computational delay, and a zero-order hold. The prefilter attenuates the analog input signal high-frequency components to suppress "aliasing" during the analog-to-digital conversion. The computational delay is the delay associated with the input, the processing, and the output of a signal through the computer. Finally, a zero-order hold adds one-half the computing interval caused by the sample-and-hold

characteristics. The last delay represents an average value for that portion of the equipment which includes the DAC. For the prefilter setting of this study, the described hardware characteristics create an average time delay from input to output of 1.5 times the update interval. This delay has an average value of about 47 msec which becomes part of the delay in the visual-scene presentation. The delay due to the scene generation equipment for elevation and azimuth line-of-sight angles to the target was small as was the delay due to the televised display of the scene to the subject. Motion cue presentation like the visual display also has the 47 msec time delay. In addition, the motion-base mechanical drive system has those time lags after compensation described in reference 5. These motion-base lags are, of course, a function of frequency. The lags expressed as an equivalent time delay were of the order of 50 msec when based on the pursuit aircraft longitudinal short period of frequency of 2.83 rad/sec. (See table X, ref. 3, for further information.)

PILOT'S TASK

Primary Task

The primary task, as in references 2 and 3, was to track visually, using a reticle, a target aircraft that was performing a sinusoidal oscillation in altitude. The oscillation had an amplitude of 30.48 m and a frequency of 0.21 rad/sec (a period of 30 sec). Precognitive control related to the sinusoidal nature of the target motion should be impossible at frequencies below 0.63 rad/sec (ref. 8) and consequently is of no concern in this study. The pursuit aircraft automatically maintained a 182.88-m separation distance behind the target aircraft. The pursuit aircraft could maneuver in the remaining five degrees of freedom and was controlled through the use of a two-axis finger-tip controller.

Audio Side Task

The audio side task used to increase the subject's workload was an application of the critical instability tracking task of Jex and others (for example, refs. 9 to 11). The audio task used is depicted in figure 5. The task required that the subject try to maintain a constant 1200-Hz audio signal by operating a thumb wheel with his left hand. The thumb wheel revolved freely and was not spring loaded. The audio signal was driven with the output of an unstable first-order linear system over a range of 500 to 1900 Hz mechanized to be hard limited. The instability was set at a subcritical level to require frequent but not continuous attention. As was pointed out in reference 11, increasing the instability increases the attention required of the subject.

The audio task included a memory update in the form of a reference tone (1200 Hz) that was provided to the subject as a pulse of short duration at fixed intervals during the run. The time setting was adjustable depending on the subject and instability value. Typical values used were 1/4-sec pulse duration at 10-sec intervals. Insertion of the reference tone was controlled by a switching circuit operated by the digital computer as indicated in figure 5.

All subjects used in the present study had normal hearing. Reference 12 indicates that for normal hearing the just-noticeable difference in the frequency range around 1000 Hz is about 0.3 percent. Thus, subjects should be able to discriminate frequency changes of the order of 3 to 5 Hz.

TEST PROGRAM

The basic aircraft of reference 3 was used for the primary tracking task throughout this investigation. The basic aircraft is defined by the parameters listed in table I. Three main factors were varied during the study: time delays, motion conditions, and pilots. Auxiliary tests were performed initially to establish an appropriate value for the instability setting for the audio side task. Time delays in visual and motion cues presentation were varied in multiples of 31.25 msec because this was the update interval of the series digital computer used. Data were collected for 0, 4, 8, 12, and 16 units of delay added to the simulation. This spacing was chosen to correspond to that used in reference 3. Note that with the motion base active, the same value of delay was substituted into the visual and motion cues.

Two types of motion conditions were used in this study; fixed base and motion base. The motion-base condition used in this study was the "full-motion" condition of reference 3 which provides motion in four degrees of freedom; roll, pitch, heave, and sway. There was no yaw motion because reference 2 indicated that the rudder pedals were never used, and aircraft yawing due to aileron deflection provided cues below threshold for this task. There was no surge motion because the longitudinal distance between the two aircraft was held constant throughout the study, and the pursuit aircraft pitch attitude changes were small (less than $\pm 5^\circ$). Since the pitch signal was small, neither washout nor scaling was required. The roll motion and the lateral motion were employed in a coordinated manner (ref. 13), primarily in an attempt to remove the false cue caused by the gravity component during the performance of a coordinated turn in a simulator. The heave motion employed second-order linear filtering. The values used for the filter or washout parameters are those employed in reference 3 and are presented in table II.

Two subjects were used in this study. They were also used in the study of reference 3 and were designated in that study as subjects A and C. For consistency, this labeling is retained in this paper. They were chosen for the present tests because their performance differed widely in the previous study. Subject A was an engineer with considerable experience in flight simulation and subject C was a research test pilot. Most of the exploratory work with the audio side task was done with subject A. Subject A was also the principal subject in reference 3. In determining acceptable time delay values, however, both subjects were used an equal amount.

DATA ANALYSIS

The pilot performance measures used in the current study and in reference 3 include the rms values (over the 2-min flight) of the vertical and lateral displacements of the center of gravity of the target aircraft from that of the pur-

suit aircraft. The rms values of the aileron and elevator control inputs were also collected. The principal performance measure for the visual tracking task, however, was the total tracking error which is the sum of the vertical and lateral center-of-gravity displacements. This particular parameter was the choice in the present study because it was the principal measure used in reference 3. Side task results consist of rms values for the thumb-wheel input and the tone error. Also used as a performance measure is the pilot gain K_p .

Each performance measure was examined statistically. An analysis of variance (ANOV) was conducted to determine whether any of the experimental factors or interactions of these factors were significant. (See ref. 14.) If the ANOV indicated a significant effect for a given factor, a t-test was performed to determine which levels of the factor differed significantly from the control level. The t-test treated each factor (i.e., time delay and motion condition) separately. That is, the standard error estimate used in the t-tests for time delays was based on data pooled over all time delays for a given motion condition. In like manner the standard error used in the t-tests for motion effect was based on data pooled over each motion condition for a given time delay.

RESULTS AND DISCUSSION

A number of tests were made using only the audio task to establish the maximum level of instability that a subject could control. Next, fixed-base tests for the primary tracking task alone and in combination with the audio task were performed for the zero time delay condition. Several instability values, less than the maximum, were tried. From this information a particular instability value was selected for the time delay study for each subject. Results and discussion of these preliminary tasks are presented in appendixes B and C. Appendix B is concerned with the side-task-only results and appendix C is concerned with workload establishment. From the considerations in the appendixes, the instability level λ chosen for subject A was 2.0 sec^{-1} and for subject C was 0.5 sec^{-1} . In both instances the subjects were found to be fully occupied. An important advantage in the use of the audio side task over the tapping task in references 2 and 3 was in assuring that the subjects were operating at their full capacity as shown by quantitative data.

Time Delay, Motion Cue, and Pilot Effects

Time histories of typical flights performed by subject A under fixed-base conditions and under motion-base conditions are presented for reference in figures 6 and 7, respectively, for 8 units of time delay. The motion-base commands for the time histories presented in figure 7 are presented in figure 8.

Subject A.—The statistical data for the two-factor experiment (motion and delay) using the primary subject are presented in table III. The ANOV indicated that motion and delay are statistically significant at the 5-percent level for most of the directly measured performance parameters; the only exception is the effect of motion cues on elevator input. Consequently, a t-test was performed on each factor. In the case of the time delay factor, zero delay was the obvious choice for the control level, and the t-test was used to determine which of

the other time delays was significantly different from the control. The rms performance measures of the primary task (total error, vertical error, horizontal error, aileron control input, and elevator control input) and the performance measures of the side task (audio tone tracking error, thumb-wheel deflection, thumb-wheel input frequency, and pilot gain K_p) are plotted as functions of time delay in figure 9 for the fixed-base condition and in figure 10 for the motion-base condition. Each point in the figures represents the mean of 10 data runs. The fairing of the data points is used to help visualize the statistical significance of the time delays. If the second data point at 4 units of delay is not significantly different from the zero delay point at the 5-percent level of significance, the line continues at the original value. For succeeding time delays the line continues until the 5-percent significance level is reached at which time the line is faired to the data point. The main purpose of the fairing is to show the break point at which the performance begins to degrade. Consequently, the lines are not extended beyond the first significantly different data point even though the t-test was applied at all time delays. The relative effect of motion (fig. 10) at a given time delay is denoted by the use of solid symbols. When the performance with motion is significantly different at the 5-percent level from that with no motion, the symbol is solid.

Increasing time delay generally causes a degradation in pilot performance. This effect is evident in all primary task performance measures. Total error $\bar{e}_v + \bar{e}_h$ is the principal performance measure selected in the present study as in reference 3 for determining the value of acceptable time delay τ_{accept} . The value for τ_{accept} denoted by the break point is 8 units of delay with or without motion. A number of other primary and side task performance measures also show a break point that occurs at 8 units of time delay. There are, however, some measures with break points that differ from 8 units of delay. These latter break points differ no more than one increment in the time delay grid employed in this study. It is interesting to note that pilot gain K_p is the only parameter that shows no break point. This infers that subject A was responding to the side task in a similar manner at all values of time delay.

Motion effects can be obtained by comparing figures 9 and 10. As indicated earlier, significant effects are designated in figure 10 with solid rather than open symbols. For example, the results for total error show a significant motion effect at all time delays. This significance occurs because of the reduced tracking error obtained with motion. Other primary task parameters show that motion was significant at only a few values of time delay. It is interesting to note that motion effects involve mainly the primary task parameters and have little influence on the side task parameters. From a subjective standpoint, motion is an important factor at all time delays, and the time delays themselves are noticeable at about 4 units of delay.

Subject C.—The statistical data for the two-factor experiment (motion and delay) using subject C are presented in table IV. The ANOV indicated that motion and delay are statistically significant at the 5-percent level for the primary task performance measures. Consequently, a t-test was performed on each factor as was done for subject A. The rms values of the primary task and side task parameters are plotted in figure 11 as functions of time delay for the no-motion condition and in figure 12 for the motion condition.

Of particular interest in this study are the results for total tracking error since this was the performance parameter used for selecting the value of acceptable time delay. The value of τ_{accept} denoted by the break point is 8 units of delay with or without motion. This is also the value obtained for subject A.

Motion effects for subject C are designated by the solid symbols in figure 12. The data show that the effect of motion on the primary task parameters occurred only at the largest value of time delay except for the control inputs. Control input magnitudes are considerably reduced at all delays when motion is present. It should be noted that the heave scaling was reduced for subject C in comparison with that used for subject A. (The same scaling change was used in ref. 3.) Reduced scaling was required for subject C in order to keep the simulator from encountering the operating limits of the motion base. Observation of the simulator motions, however, indicated that comparable physical movement of the base occurred for the two subjects.

As indicated in the ANOV of table IV and in figures 11 and 12, the effect of time delay was not statistically significant on the side task parameters. This insignificance is denoted in these figures by an unbroken straight line. Motion effects, however, are significant on two parameters (tone error and thumb-wheel output), as indicated by the solid symbols in figure 12. Also, the ANOV in table IV(i) indicates that motion has a significant effect on pilot gain. For this particular parameter, the less powerful t-test did not identify the delay values where the significance occurs; however, one value was close to the significant value (1.836 compared to 2.101). Although these side task results differ from those of subject A in figures 9 and 10, subject C was fully occupied as indicated by the results in appendix C.

Side task effects.— Subject A and subject C much prefer the audio task to the tapping task employed in references 2 and 3. There are, however, subject differences in the use of the audio task. Some subjects can accept the audio task as a true side task. Since the audio task requires frequent attention, other subjects may use the audio task as the primary task and the visual task as the side task. Still others may accept both tasks as a combined entity. These differences manifest themselves in whether a time delay effect and a motion effect appears in the audio task performance parameters. Choice of the instability level for use in the audio task is a crucial factor in establishing the experiment and is, of course, subject dependent. Further discussion of the use of the audio task is given in appendix C.

Comparison With Previous Results

A detailed comparison of the primary performance results obtained with the audio task and the tapping task of reference 3 is provided in reference 4. (Ref. 4 examines the effect on pilot performance of several side tasks including the tapping and audio tasks.) Consequently, only two parameters, total tracking error at $\tau = 0$ and acceptable time delay values, are discussed here. These data are summarized in figure 13.

In figure 13(a), tracking error results for subject A show a large reduction in magnitude (significant at the 5-percent level) in going from the tapping side task to the audio side task (circle and square symbols). Unfortunately, the tapping task data, as pointed out in reference 3, were obtained with poor lateral trim conditions. An additional data set at $T = 0$ is available in table IX of reference 3 for subject A with motion (triangle). This set was obtained with good lateral trim. A statistical analysis using the three data sets for subject A shows a statistical significance at the 5-percent level for

- (1) The effect of lateral trim (compare circle and triangle for tapping task)
- (2) The effect of side task (compare triangle for tapping task with circle for audio task)

Although a comparison between tapping and audio tasks cannot be made for fixed-base conditions for subject A, the inference from the data shown is that such a comparison would also be statistically significant. Results for subject C for the tapping and audio tasks, however, are not significantly different. These subject differences are believed to be due to the manner in which each subject used the tapping side task in reference 3. Of the four subjects tested, subject A had the largest side task output in counts, and subject C had the lowest output. Thus, as expected, the level of tracking error for subject A is the lowest with the audio task since this side task introduces no visual interference in tracking the target. For subject C, tracking error for the tapping task for both fixed-base and motion-base conditions were about the same level as those for the audio task, principally because the subject addressed the tapping side task conservatively as indicated by the low count output.

A summary of acceptable time delay values determined from a statistical analysis of total tracking error results for tests using the audio side task and the tapping task of reference 3 is given in figure 13(b). An examination of the tapping results shows that, with the addition of motion cues, larger time delay values could be handled before a performance degradation occurred for three of the four subjects tested. Subject C shows no-motion effect probably because of the conservative and inconsistent manner in which he addressed the tapping side task. In general, it appears that motion cues replace some of the information loss due to the visual interruption in viewing the target aircraft caused by performing the tapping task. For subject A this increment in t_{accept} due to motion is about 4 units of time delay. Replacing the tapping task with the audio task allows subjects unrestricted visual observation of the target aircraft. The increase in target observation time results in an increase for subject A in t_{accept} by 4 units. (Compare fixed-base tapping task with fixed-base audio task.) This increment in t_{accept} is comparable to that for addition of motion when using the tapping task. This reasoning suggests that a trade-off exists between visual observation time and motion cues.

When motion cues are added to the condition with the audio side task for subject A, further increases in t_{accept} were not obtained. This fact indicates that, for the test grid employed, t_{accept} is near its maximum value for the primary and side task combination tested. Also worth observing in the table

is the fact that for the audio side task, T_{accept} values for subject A and subject C are the same. Thus, subject differences are eliminated when the audio side task is used. Further examination of T_{accept} values in figure 13(b) shows that subject differences are eliminated when using the tapping side task with motion as well as when using the audio task. Also, a T_{accept} value of 8 units of delay is the same for tests with the audio side task. These latter observations suggest T_{accept} may be invariant with subjects and also with type of side task used to increase pilot workload as long as the side task does not directly impinge on the subject's ability to perform the primary task. For such circumstances, T_{accept} would then be simply a function of the task to be performed and the level of task difficulty employed. Further tests are required to verify these exploratory results.

It is important to note that the time delay grid employed in the present paper is rather coarse (4 units of delay). Use of a finer time delay grid may result in some modification to the T_{accept} values tabulated.

CONCLUDING REMARKS

An experimental study has been made to determine the effect of time delays in the visual and motion cues on pilot tracking performances in a flight simulator. Acceptable time delay is defined in this paper as the largest amount of additional delay that can be inserted simultaneously in the visual and motion cues of the simulator before a performance degradation occurs. A statistical analysis of the data was made to establish this value. An audio side task was used to assure the pilot was fully occupied at all times. This study extends the investigation of references 2 and 3 by providing data on a single aircraft for two subjects using a more closely controlled side task. Results of this study indicate the following:

1. Within the test grid employed, the value of acceptable time delay determined only from the single performance parameter of total tracking error was 8 units of time delay (about 250 msec) for both subjects with both fixed- and motion-base conditions. Thus, subject differences are eliminated and there are no motion effects on acceptable time delay when using the audio side task. When the side task employed forces a visual interruption in primary task observation, as did the tapping task of reference 3, then motion cues can provide an increase in acceptable time delay.

2. Significant effects of time delay at the 5-percent significance level were obtained for both subjects on all primary performance parameters (c.g. displacements and control inputs). Also, significant effects of time delay were obtained on most side task parameters for one subject and none for the other.

3. Significant motion effects at the 5-percent significance level were obtained on most primary task performance parameters at the higher values of time delay for both subjects. In addition, one subject showed a motion effect across all time delays for some primary task performance parameters.

4. The audio side task provides statistical data that assures the pilot is fully occupied at all times. The audio side task permitted the subject to allocate full visual attention to the primary tracking task.

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APPENDIX A

EQUATIONS OF MOTION

The linearized equations used in this study for the pursuing aircraft are written about the aircraft body axes and are:

$$a_x = 0 \quad (A1)$$

$$a_y = Y_{\beta} \beta V_{x,0} \quad (A2)$$

$$a_z = -(L_{\alpha} \alpha + L_0) V_{x,0} \quad (A3)$$

$$\dot{p} = L_p p + L_{\beta} \beta + L_r r + L_{\delta_a} \delta_a \quad (A4)$$

$$\dot{q} = M_{\alpha} \alpha + M_q q + M_{\delta_e} \delta_e \quad (A5)$$

$$\dot{r} = N_r r + N_{\beta} \beta + N_p p + N_{\delta_r} \delta_r \quad (A6)$$

In equations (A2) and (A3)

$$\alpha = \tan^{-1} \frac{w}{u}$$

$$\beta = \sin^{-1} \frac{v}{V}$$

$$V = (v_x^2 + v_y^2 + v_z^2)^{1/2}$$

and

$$u = l_1 v_x + l_2 v_y + l_3 v_z$$

$$v = m_1 v_x + m_2 v_y + m_3 v_z$$

$$w = n_1 v_x + n_2 v_y + n_3 v_z$$

Aircraft orientation and velocity relative to inertial space are required to generate the proper position of the target relative to the pursuer (for display purposes). The orientation of the pursuer in space is specified by Euler angles. These angles are determined from body angular rates by

$$\dot{\psi} = p + q \sin \psi \tan \theta + r \cos \psi \tan \theta$$

APPENDIX A

$$\dot{\theta} = q \cos \varphi - r \sin \varphi$$

$$\dot{\psi} = (r \cos \varphi + q \sin \theta) \frac{1}{\cos \theta}$$

Inertial accelerations are given by

$$\dot{V}_x = l_1 a_x + m_1 a_y + n_1 a_z$$

$$\dot{V}_y = l_2 a_x + m_2 a_y + n_2 a_z$$

$$\dot{V}_z = l_3 a_x + m_3 a_y + n_3 a_z + g$$

Direction cosines are defined as follows:

$$l_1 = \cos \psi \cos \theta$$

$$l_2 = \sin \psi \cos \theta$$

$$l_3 = -\sin \theta$$

$$m_1 = \cos \psi \sin \theta \sin \varphi - \sin \psi \cos \varphi$$

$$m_2 = \sin \psi \sin \theta \sin \varphi + \cos \psi \cos \varphi$$

$$m_3 = \cos \theta \sin \varphi$$

$$n_1 = \cos \psi \sin \theta \cos \varphi + \sin \psi \sin \varphi$$

$$n_2 = \sin \psi \sin \theta \cos \varphi - \cos \psi \sin \varphi$$

$$n_3 = \cos \theta \cos \varphi$$

Initial conditions were $V_{x,0} = 304.8$ m/sec; $V_{y,0} = V_{z,0} = 0$; $\psi_0 = \theta_0 = \varphi_0 = 0$; and $p_0 = q_0 = r_0 = 0$.

APPENDIX B

SIDE TASK ONLY

General Comments

In controlling a first-order unstable system, the pilot is constrained to operate in a purely proportional error correcting mode. With no forcing function input, as used for the setup in this paper, the pilot gain can be represented simply by

$$K_{\star} = \frac{\text{rms } (\delta_s)}{\text{rms } (B)}$$

where δ_s is the thumb-wheel output and B is the input voltage driving the voltage control oscillator and, hence, is the sound frequency. A derivation of the applicable system equations for the audio side task is contained in appendix D. Also presented there is a brief derivation for the gain limits as predicted by simple theory. These limits are illustrated in figures 14 and 15.

A summary of the data for side task only is given in table V. Means were computed and tabulated for rms (B), rms (δ_s), and pilot gain K_{\star} for various test conditions. Replicates were obtained for most conditions; however, the number of runs varied widely. It should be noted that most of the data were obtained with subject A; only a small amount were taken with subject C.

Effect of Reference Pulse Width and Spacing

The audio side task used in the present paper required that the subject make a mental comparison between the signal tone and a reference tone (i.e., 1200 Hz) that he must remember during the run. To update the subject's memory, a short pulse of the reference tone was inserted periodically in the audio cue supplied the subject. The reference tone must be given frequently enough to reinforce the subject's memory or the remembered reference frequency may deviate from 1200 Hz. If given too frequently, however, the task difficulty is increased because of the total amount of blanking of the tracking signal during the run. To establish the spacing value used in these tests, several runs were made with different pulse frequencies. From these a spacing of 10 sec was selected as a reasonable value. This value was used for all data runs presented in this paper.

The width of the reference pulse must also be considered. The pulse must be long enough for the subject to detect the reference even when small differences exist but not so long that the tone signal would change appreciably during the blanking period. As would be expected, therefore, the pulse width is sensitive to the numerical value of the first-order instability λ used. For example, increasing the instability λ increases the rate and amount of signal departure during the blanking period. To avoid loss of control, the pulse width must be reduced. For subject A, a value of 1/4 sec was selected as appropriate

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for use in these tests, especially when the side task was combined with the primary task. For subject C, the instability settings employed were not as large as for subject A; and, consequently, a pulse width of 1/2 sec was used.

Effect of Instability

Side task results for different instability levels are given in table V and in figure 14. Measurements taken early in the test program and late in the test program are shown for subject A. Also shown are values for subject C.

From an examination of figure 14, it appears that the results of subject A taken late in the test program show an improvement over the early measurements possibly due to learning curve effect. Specifically, rms tracking error is less, rms control wheel inputs are less, and pilot gain is higher. Results for subject C were obtained for a lower instability setting than were documented for subject A because subject C resisted going to higher levels of instability. This resistance is primarily the result of the fairly large audio tracking error \bar{B} that subject C had at the lower instability setting.

Theoretical gain limits were computed using the theory as given in appendix D. These curves are shown in figure 14. Of major interest is the instability value where the data curves cross the theoretical boundary. These points indicate the maximum instability value that can be handled by the subject. Gain values are shown for larger instability levels simply because the audio task was arranged so that an audio cue was always available to the subject. Thus, recovery from loss of control could be accomplished but with a large penalty in tracking error score. In the usual arrangement of the critical task used by Jex and others, this feature was not included, and departure due to loss of control was very distinct. It is also of interest to note that most combined primary and side task data taken with subject A were for $\lambda = 2.0$. This value is, of course, less than the maximum instability level of 2.5 obtained from the early side-task-only tests and the 3.5 value indicated from the later tests. The combined task instability setting of 2.0 was used, however, only after some experience was gained with the audio task. Thus, the setting $\lambda = 2.0$ is a reasonable choice since a value approaching critical could cause the subject to shift his primary concern from the visual tracking task to the audio task.

APPENDIX C

WORKLOAD ESTABLISHMENT

For the experiment to be successful it is necessary that the subject, when performing both tasks, be fully occupied at the zero time delay condition. This assures that the subject has no reserve capability on which to draw when additional time delays are inserted in the simulator cues. Consequently, if a given time delay impacts the tracking task, it will appear as a degradation in performance. Thus, to be sure of the loading situation for the zero time delay case, an examination of the data is undertaken here. The results of interest are summarized in tables VI and VII for subject A. Results for subject C are given in tables VIII and IX. The data presented are for fixed-base and motion-base conditions for the audio side task instability level used by each subject during the time delay study. Also tabulated are results of tests using side task only and primary task only. Note that for these latter results only two data sets were obtained. Side-task-only data were obtained for fixed-base conditions, whereas primary-task-only data were obtained for motion-base conditions. In both cases the results were expected to be nearly identical for the other motion condition; and, consequently, the data are used interchangeably in the tables. When so used, the data are appropriately marked.

A statistical analysis was performed on the basic data used in compiling tables VI to IX. A student t-test comparing the sample means was performed for side task only with the combined task and for primary task only with the combined task. The computed t-test values thus obtained are tabulated for each entry. The significance at the 5-percent level and 1-percent level is also designated. All 10 variables were examined separately.

Results for subject A, for both fixed-base and motion-base conditions, indicate that the significant effects are with the side task results. The difference shown for the primary task variables appear to be due to sampling effects. That is, there is no difference in primary task variables with and without the side task. Thus, subject A, in effect, accepts the target tracking task as the primary task. In addition, the subject's gain in operating the side task remains nearly the same and indicates that the subject is attacking the side task in the same manner for the combined task as he did for the side-task-only tests. The degradation shown in \bar{B} and $\bar{\sigma}_g$ for the side task when the primary task is added shows that the subject is fully occupied. If the subject were not, his performance on the side task would be more nearly like that of the side task alone. What is shown, therefore, is exactly the results that would occur with the pilot fully occupied and with insufficient time to adequately address the side task.

The fixed-base results in table VIII for subject C show that his major concern was with the side task since for the three audio parameters no significant differences are indicated. Also, since significant differences are listed for the primary task, the inference can be drawn that subject C accepted the audio task as the primary task. This would not be an uncommon experience because the audio task demands constant attention in order to achieve an acceptable performance score. The motion-base results in table IX show similar

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effects; however, with motion active, the subject's side task gain shows a change indicating that he addressed the side task more aggressively in the combined task than he did for the side-task-only tests. The improved gain also manifested itself in lower audio tracking error scores. As in the fixed-base condition, the data imply that subject C accepted the side task as the primary task. It is important to note, however, that for the combined task for both motion conditions, a degradation in performance occurred in one of the tasks. Thus, subject C, like subject A, was fully occupied for the combined task at the zero time delay condition.

Additional data for the combined task were obtained for subject A at different levels of instability early in the test program. These tests were all made under the fixed-base condition. A comparison of all side task results for the combined task with the side-task-only curves of figure 14 are presented in figure 15. Note that for an instability value $\lambda = 2.0$, both fixed- and motion-base results given in tables VI and VII are shown. An examination of the figure shows that the pilot gain values were within the boundaries and that they approximate the values of the side-task-only curve. Note that for $\lambda = 3.0$ the pilot gain is on the lower boundary indicating approaching instability with further increases in λ . This particular λ value can be interpreted as the upper instability limit for use with the side task. Gain value K_s was the form in which the data were obtained in this experiment. As indicated in appendix D, the additional plot K_s/λ was included in figure 15 to permit direct comparison with other data (i.e., ref. 11) if desired.

APPENDIX D

AUDIO TASK THEORY

A block diagram with the pilot in the loop is given in figure 16. The transfer functions of the thumb wheel, the voltage controlled oscillator, and the speakers are represented by the simple gains K_W , K_{VCO} , and K_S , respectively. Transfer functions for the pilot and the controlled element, which was a first-order unstable system, are tabulated. The diagram specifies the operational condition that the subject remember the reference tone and perform a mental subtraction to establish the error signal. The reference tone used was 1200 Hz and was produced when the voltage B was zero.

A simpler but equivalent diagram for analysis purposes is given as figure 17. Note that an equivalent pilot gain K_* can be defined as

$$K_* = K_P K_W \quad (D1)$$

Values of K_* can then be computed from

$$K_* = \left| \frac{\delta_S}{B} \right| \quad (D2)$$

Since the rms data for δ_S and B were obtained for every data run, a value of K_* was calculated instead from

$$K_* = \frac{\text{rms } (\delta_S)}{\text{rms } (B)} \quad (D3)$$

The plant representation tabulated in figure 17 can be obtained easily from figure 5 by noting

$$\dot{B} = \delta_S + \lambda B \quad (D4)$$

where λ is the potentiometer setting for the first-order system. Taking the Laplace transform of equation (D4) gives

$$Y_C = \frac{B(s)}{\delta_S(s)} = \frac{1}{s - \lambda} \quad (D5)$$

The pilot representation was listed in figure 17 as

$$Y_P = K_P e^{-\tau_e s} \quad (D6)$$

where τ_e is an effective time delay. Representing the time delay with a Padé approximation yields

$$Y_P = K_P \frac{(2 - \tau_e s)}{(2 + \tau_e s)} \quad (D7)$$

The open-loop transfer function $G(s)$ for the system in figure 17 is therefore

$$G(s) = K_P K_W \frac{(2 - \tau_e s)}{(2 + \tau_e s)(s - \lambda)} \quad (D8)$$

$$G(s) = K_* \frac{(2 - \tau_e s)}{(2 + \tau_e s)(s - \lambda)} \quad (D9)$$

The characteristic equation of the system then can be written as

$$1 + G(s) = 0 \quad (D10)$$

Substitution for $G(s)$ yields

$$s^2 + \left(\frac{2}{\tau_e} - \lambda - K_* \right) s + \frac{2}{\tau_e} (K_* - \lambda) = 0 \quad (D11)$$

The gain limits for system stability can be evaluated from equation (D11). The upper limit is determined by

$$\frac{2}{\tau_e} - \lambda - K_* = 0 \quad (D12)$$

because this gives the value of the roots as they cross the imaginary axis in a root locus plot. The lower gain limit is determined from

$$K_* - \lambda = 0 \quad (D13)$$

since this gives one root at $s = 0$.

To establish the upper gain boundary, a value of effective time delay must be selected for use with equation (D12). Of the several values considered, a τ_e of 2/7 sec was chosen and used in this investigation.

The audio task used in this paper is a direct application of the "critical" task used by Jex and others. A thorough description and discussion of the critical task and its use as a side task is given in references 9, 10, and 11. As pointed out in reference 11, the controlled element is usually of the form $\lambda/(s - \lambda)$. For the setup used in this text, the controlled element was $1/(s - \lambda)$. Thus, the pilot gain values computed for the two cases differ by a scale factor. Gain results are given in figures 14 and 15 in both forms in order to permit a direct comparison with other "critical" task measurements, if so desired.

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TABLE I.- PARAMETERS OF "BASIC" AIRCRAFT

[Data from ref. 3]

Parameter	Value
L_{α}	2.0
$L_{\dot{\alpha}}$	.0322
M_{α}	6.0
$M_{\dot{\alpha}}$	-7.0
M_{δ_e}	-10.0
L_{ξ}	-42.14
L_p	-2.74
L_r	2.058
N_{β}	5.544
N_p	.0148
N_r	-.2782
Y_{β}	-.1589
L_{δ_a}	-10.0
N_{δ_a}	0
N_{δ_r}	-10.0

TABLE II.- MOTION-BASE DRIVE EQUATIONS AND GAIN VALUES USED

[Data from ref. 3]

(a) Motion-base drive equations

$$\theta_C = \theta + K_0 \dot{\theta}$$

$$\dot{P}_K = K_1 P - K_2 P_K - K_3 a_Y$$

$$\ddot{Y}_K = K_4 a_Y + K_5 P_K - K_6 \dot{Y}_K - K_7 Y_K$$

$$\varphi_C = K_8 \varphi + K_9 P_K + K_{10} \dot{P}_K + K_{11} \dot{\varphi}$$

$$Y_C = Y_K + K_{12} \dot{Y}_K + K_{13} \ddot{Y}_K$$

$$\ddot{z}_K = K_{14} \dot{V}_z - K_{15} \dot{z}_K - K_{16} z_K$$

$$z_C = z_K + K_{17} \dot{z}_K + K_{18} \ddot{z}_K$$

(b) Gain values

Gain	Subject A	Subject C
a_{K0}	0.15	0.15
K_1	.50	.50
K_2	.322	.322
K_3	.01	.01
K_4	1.00	1.00
K_5	32.2	32.2
K_6	1.134	1.134
K_7	.67	.67
K_8	0	0
K_9	1.0	1.0
a_{K10}	.15	.15
a_{K11}	0	0
a_{K12}	.15	.15
a_{K13}	.007	.007
K_{14}	.15	.05
K_{15}	2.02	2.02
K_{16}	2.01	2.01
a_{K17}	.1333	.1333
a_{K18}	.007	.007

^aHardware compensation parameters.

TABLE III.- SUMMARY OF DATA FOR MOTION/DELAY INTERACTION WITH SUBJECT A

(a) Total error

rms total error in meters for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	3.853	4.275	3.989	5.976	6.180
	4.016	3.892	3.689	5.182	5.918
	3.634	3.474	4.162	4.320	6.027
	3.879	3.631	3.634	4.127	4.233
	3.601	3.638	3.887	4.372	5.585
	3.734	3.843	3.856	4.179	5.711
	3.511	3.931	3.857	4.489	5.074
	3.661	3.759	3.741	4.346	4.604
	3.387	3.935	3.705	4.516	5.027
	3.552	3.741	3.835	4.662	4.600
$\bar{\epsilon}_v + \bar{\epsilon}_h$	3.683	3.812	3.836	4.617	5.300
σ	.190	.220	.157	.563	.681
t(time delay)	Control	.69	.81	b4.95	b8.55
Motion					
	3.405	3.432	3.936	4.091	3.880
	3.834	3.672	3.613	4.462	4.907
	3.549	3.675	3.777	3.913	4.481
	3.432	3.686	3.519	3.317	4.255
	3.329	3.328	3.417	4.077	4.303
	3.460	3.519	3.505	3.546	3.476
	3.243	3.301	3.492	3.621	4.487
	3.387	3.492	3.512	3.669	3.933
	3.255	3.262	3.357	3.538	3.970
	3.449	3.338	3.533	3.328	3.798
$\bar{\epsilon}_v + \bar{\epsilon}_h$	3.434	3.470	3.565	3.756	4.150
σ	.170	.165	.172	.370	.417
t(time delay)	Control	.29	1.04	b2.56	b5.69
t(motion)	b3.05	b3.93	b3.68	b4.04	b4.53

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOV F	b65.53	b38.37	b6.61	---
Fcritical	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE III.- Continued

(b) Vertical error

rms vertical error in meters for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	3.138	3.167	2.983	3.941	4.237
	3.000	3.061	2.919	3.441	4.217
	2.847	2.855	3.119	3.013	4.377
	3.038	2.983	2.941	3.115	3.336
	2.911	2.893	2.961	3.236	3.621
	3.092	2.752	2.936	3.115	3.795
	2.837	2.983	2.880	3.251	3.888
	2.850	3.108	2.891	3.121	3.215
	2.765	2.862	2.943	3.161	3.867
	2.813	2.921	2.874	3.242	3.531
$\frac{\bar{e}_v}{\sigma}$	2.929	2.959	2.945	3.264	3.808
σ	.129	.127	.071	.264	.390
t(time delay)	Control	.29	.15	b3.28	b8.62
Motion					
	2.969	2.902	2.952	3.230	3.154
	3.102	2.931	2.934	3.425	3.644
	2.869	2.940	3.058	2.915	3.472
	2.788	2.820	2.835	2.813	3.282
	2.839	2.783	2.907	2.882	3.325
	2.913	2.882	2.911	2.922	2.822
	2.711	2.675	2.897	2.890	3.420
	2.757	2.854	2.791	2.990	2.962
	2.663	2.782	2.740	2.709	3.211
	2.794	2.759	2.795	2.738	3.049
$\frac{\bar{e}_v}{\sigma}$	2.840	2.833	2.882	2.951	3.234
σ	.130	.084	.094	.221	.248
t(time delay)	Control	.10	.55	1.47	b5.21
t(motion)	1.53	b2.59	1.69	b2.87	b5.26

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOV F	b33.65	b36.55	b5.78	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE III.- Continued

(c) Horizontal error

rms horizontal error in meters for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.715	1.109	1.006	2.035	1.942
	1.016	.831	.770	1.741	1.700
	.787	.619	1.043	1.305	1.650
	.841	.648	.694	1.012	.897
	.690	.744	.926	1.136	1.964
	.642	1.092	.919	1.065	1.916
	.675	.948	.976	1.237	1.186
	.811	.651	.851	1.225	1.389
	.622	1.073	.761	1.355	1.160
	.739	.820	.961	1.420	1.069
$\frac{\bar{e}_h}{\sigma}$	0.753	0.853	0.891	1.353	1.487
σ	.117	.192	.117	.316	.397
t(time delay)	Control	.88	1.21	b5.29	b6.47
Motion					
	0.435	0.529	0.986	0.861	0.726
	.732	.741	.679	1.037	1.263
	.681	.735	.719	.999	1.010
	.644	.866	.684	.504	.973
	.490	.544	.509	1.194	.978
	.547	.638	.594	.624	.654
	.532	.626	.595	.731	1.068
	.630	.638	.720	.679	.971
	.592	.480	.617	.830	.758
	.655	.579	.738	.590	.749
$\frac{\bar{e}_h}{\sigma}$	0.594	0.638	0.684	0.805	0.915
σ	.092	.116	.128	.221	.189
t(time delay)	Control	.63	1.29	b3.01	b4.58
t(motion)	b3.40	b3.05	b3.77	b4.50	b4.12

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	b64.72	b23.37	b4.95	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE III.- Continued

(d) Aileron deflection

rms aileron deflection ($\times 10^2$), rad, for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	1.158	1.762	2.034	3.675	3.739
	1.785	1.930	1.743	2.430	1.364
	1.619	1.560	1.694	2.862	2.381
	1.634	.874	1.146	1.168	.960
	1.106	1.077	1.466	2.249	2.001
	.935	1.111	1.861	1.339	3.443
	1.122	1.586	1.970	1.966	2.243
	1.094	.980	1.496	1.833	1.492
	1.711	1.859	1.109	2.323	3.378
	.812	1.543	1.468	2.528	2.510
$\frac{\delta a}{\sigma}$	1.298	1.428	1.599	2.237	2.351
t(time delay)	.353	.386	.319	.728	.942
Control		.49	1.12	b3.51	b3.94
Motion					
	1.371	1.281	1.437	1.531	1.636
	1.235	1.144	1.183	1.167	1.596
	1.288	1.050	1.095	1.794	1.622
	1.259	1.423	2.027	1.296	1.323
	1.119	1.538	1.127	2.372	2.181
	1.455	1.757	1.050	1.979	2.131
	.911	1.230	2.103	1.282	1.487
	.826	1.063	2.152	2.122	2.212
	1.301	1.624	1.626	1.946	2.118
	1.426	1.996	1.781	1.839	1.693
$\frac{\delta a}{\sigma}$	1.219	1.411	1.558	1.733	1.800
t(time delay)	.209	.316	.439	.399	.327
t(motion)	.60	.11	.23	1.92	b2.33
Control		1.23	b2.18	b3.31	b3.74

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	b5.93	b10.52	1.47	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE III.- Continued

(e) Elevator deflection

rms elevator deflection ($\times 10^2$), rad, for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.335	0.595	0.537	0.747	0.943
	.398	.371	.433	.739	.590
	.529	.534	.464	.498	.683
	.502	.478	.353	.532	.641
	.380	.399	.765	.646	1.057
	.335	.398	.433	.491	.693
	.334	.396	.470	.636	.898
	.273	.325	.330	.536	.706
	.348	.471	.363	.442	1.093
	.314	.316	.438	.586	.739
$\frac{\bar{\delta}_e}{\sigma}$	0.375	0.428	0.458	0.589	0.804
σ	.082	.090	.124	.108	.179
t(time delay)	Control	.98	1.53	b3.94	b7.90
Motion					
	0.375	0.420	0.441	0.432	0.579
	.387	.335	.381	.454	.655
	.351	.282	.365	.451	.499
	.365	.357	.498	.466	.494
	.476	.515	.477	.715	.946
	.396	.583	.389	.752	.719
	.364	.401	.678	.503	.494
	.308	.351	.579	.719	.543
	.469	.625	.597	.690	.960
	.477	.659	.549	.584	.622
$\frac{\bar{\delta}_e}{\sigma}$	0.397	0.453	0.495	0.577	0.651
σ	.058	.133	.104	.130	.176
t(time delay)	Control	.99	1.74	b3.18	b4.50
t(motion)	-----	-----	-----	-----	-----

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANC / F	0.44	b23.79	2.01	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE III.- Continued

(f) Audio task tracking error

rms audio task tracking error, volts (460 Hz/volt), for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.476	0.726	0.726	0.561	0.779
	.177	.508	.565	.625	.687
	.368	.636	.377	.499	.780
	.579	.537	.599	.445	.601
	.748	.244	.443	.419	.595
	.507	.502	.536	.560	.736
	.340	.464	.502	.318	.566
	.336	.402	.410	.527	.388
	.323	.316	.408	.476	.392
	.344	.336	.296	.527	.506
$\frac{B}{G}$ t(time delay)	0.420 .161 Control	0.467 .148 .78	0.486 .125 1.09	0.496 .087 1.25	0.603 .145 ^b 3.02
Motion					
	0.454	0.625	0.277	0.374	0.469
	.387	.480	.394	.516	.745
	.368	.260	.328	.490	.535
	.446	.334	.661	.680	.409
	.519	.689	.307	.612	.582
	.516	.814	.260	.543	.464
	.214	.208	.387	.362	.452
	.283	.221	.289	.496	.455
	.252	.376	.497	.658	.684
	.665	.422	.461	.629	.743
$\frac{B}{G}$ t(time delay) t(motion)	0.414 .134 Control -----	0.442 .208 .42 -----	0.385 .124 .45 -----	0.535 .113 1.85 -----	0.554 .128 ^b 2.14 -----

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOV F	1.01	^b 4.42	0.67	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE III.- Continued

(g) Audio task thumb-wheel deflection

rms audio task thumb-wheel deflection, volts (22.9 deg/volt), for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	1.161	1.543	1.448	1.248	1.677
	.534	1.130	1.277	1.456	1.741
	1.217	1.473	.941	1.313	1.949
	1.285	1.241	1.380	1.079	1.406
	1.565	.627	1.183	.999	1.421
	1.266	1.174	1.253	1.357	1.689
	.916	1.197	1.092	.883	1.271
	.784	.945	.948	1.221	.912
	.897	.825	.904	1.046	1.173
	.864	.817	.702	1.290	1.318
$\frac{\delta_s}{\sigma}$	1.043	1.097	1.113	1.189	1.456
σ	.300	.293	.237	.180	.309
t(time delay)	Control	.45	.58	1.22	^b 3.44
Motion					
	1.102	1.342	0.763	1.017	1.212
	1.032	1.171	1.057	1.319	1.576
	1.016	.772	.979	1.195	1.426
	1.161	.896	1.523	1.538	1.164
	1.262	1.586	.823	1.685	1.648
	1.134	1.884	.644	1.360	1.142
	.673	.633	1.127	.886	1.220
	.693	.598	.825	1.158	1.097
	.904	.891	1.208	1.575	1.525
	1.540	1.009	1.064	1.452	1.682
$\frac{\delta_s}{\sigma}$	1.052	1.078	1.001	1.319	1.369
σ	.258	.419	.255	.255	.226
t(time delay)	Control	.20	.39	2.05	^b 2.44
t(motion)	-----	-----	-----	-----	-----

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	0.90	^b 6.66	0.37	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE III.- Continued

(h) Audio task thumb-wheel input frequency

rms audio task thumb-wheel input frequency, Hz, for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.70	0.75	0.67	1.11	1.08
	.93	.65	.61	.88	1.14
	.64	.50	.63	1.04	.88
	.60	.66	.78	1.00	1.25
	.80	.75	.94	.81	.80
	.68	.69	.71	.83	.83
	.95	.66	.67	.80	.88
	.76	.57	.72	1.05	1.25
	.70	.80	.70	.97	.80
	.80	.72	.79	.84	.88
$\bar{\omega}_{\delta_s}$	0.76	0.67	0.72	0.93	0.98
$\bar{\sigma}$	.12	.09	.10	.11	.18
t(time delay)	Control	1.61	.71	b3.04	b3.94
Motion					
	0.81	0.73	0.93	1.17	0.86
	.96	.69	.99	1.01	1.14
	.81	.67	.96	1.26	1.02
	1.17	.87	1.07	.88	1.36
	.78	.88	.67	1.13	1.24
	.53	.71	1.08	.64	1.33
	.85	.86	.64	1.18	.74
	.78	.73	1.07	.91	1.08
	1.02	.65	.66	.83	1.06
	.67	.73	.71	.83	.74
$\bar{\omega}_{\delta_s}$	0.84	0.75	0.88	0.98	1.06
$\bar{\sigma}$	.18	.09	.19	.20	.22
t(time delay)	Control	1.11	.50	1.75	b2.75
t(motion)	1.19	2.03	b2.43	.69	.87

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	b8.30	b13.17	0.31	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE III.- Concluded

(i) Pilot gain, K_p

rms pilot gain, K_p , for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	2.438	2.127	1.994	2.225	2.153
	3.014	2.225	2.262	2.328	2.534
	3.306	2.317	2.498	2.630	2.499
	2.221	2.309	2.304	2.427	2.339
	2.091	2.566	2.672	2.383	2.388
	2.495	2.089	2.339	2.423	2.296
	2.694	2.578	2.174	2.776	2.244
	2.334	2.353	2.309	2.318	2.353
	2.775	2.610	2.215	2.200	2.993
	2.514	2.434	2.369	2.445	2.604
\bar{K}_p	2.588	2.361	2.314	2.416	2.440
σ	.369	.185	.183	.176	.237
t(time delay)	Control	-----	-----	-----	-----
Motion					
	2.430	2.147	2.751	2.716	2.583
	2.668	2.441	2.685	2.555	2.116
	2.759	2.973	2.982	2.441	2.667
	2.604	2.685	2.304	2.262	2.847
	2.434	2.303	3.684	2.752	2.832
	2.198	2.707	2.473	2.506	2.463
	3.152	3.156	2.910	2.450	2.702
	2.448	2.707	2.854	2.336	2.409
	3.095	2.372	2.430	2.394	2.229
	2.314	2.393	2.308	2.302	2.264
\bar{K}_p	2.610	2.588	2.738	2.472	2.511
σ	.317	.315	.413	.164	.256
t(time delay)	Control	-----	-----	-----	-----
t(motion)	.143	1.972	^b 2.970	.744	.642

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	^b 8.530	1.022	1.831	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- SUMMARY OF DATA FOR MOTION/DELAY INTERACTION WITH SUBJECT C

(a, Total error

rms total error in meters for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	4.800	5.036	5.962	6.478	11.157
	5.230	5.383	4.940	5.869	10.018
	5.849	5.255	6.300	5.522	8.350
	4.245	5.753	4.877	5.792	8.826
	3.973	4.626	4.675	5.121	6.753
	4.488	4.589	4.441	5.196	6.101
	4.343	4.195	4.437	4.950	6.297
	3.679	4.611	5.049	4.771	6.313
	4.490	4.429	5.255	5.428	9.662
	5.082	5.193	5.774	6.761	7.676
$\bar{e}_v + \bar{e}_h$	4.618	4.907	5.171	5.589	8.115
\bar{e}_v	.640	.490	.645	.647	1.779
t(time delay)	Control	.67	1.28	b2.25	b8.11
Motion					
	5.859	4.242	4.645	7.014	7.738
	4.625	5.211	4.751	7.693	8.060
	4.001	4.934	6.215	7.437	5.909
	4.745	4.664	5.191	7.578	6.143
	3.659	4.211	6.672	5.206	4.594
	3.951	5.776	5.514	5.046	4.842
	3.955	4.122	4.413	4.568	4.964
	4.342	4.098	4.251	4.341	4.664
	4.104	4.440	4.950	4.511	5.113
	4.115	3.722	5.045	4.318	5.450
$\bar{e}_v + \bar{e}_h$	4.336	4.542	5.165	5.771	5.748
\bar{e}_v	.627	.614	.774	1.465	1.244
t(time delay)	Control	.46	1.84	b3.19	b3.14
t(motion)	1.00	1.47	.02	.36	b3.45

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	b7.77	b16.95	b5.60	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- Continued

(b) Vertical error

rms vertical error in meters for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	3.410	3.607	4.191	4.212	7.068
	3.453	3.921	3.153	4.008	6.259
	4.208	3.365	3.807	3.756	5.137
	3.252	3.886	3.654	3.951	5.168
	3.256	3.482	3.836	3.825	4.524
	3.204	3.382	3.527	3.569	4.341
	3.217	2.726	3.114	3.520	4.087
	2.872	2.899	3.365	3.197	3.828
	3.357	3.094	3.810	3.403	6.512
	3.177	3.773	3.941	4.490	5.335
$\bar{\epsilon}_v$	3.341	3.413	3.640	3.793	5.226
σ	.344	.408	.348	.390	1.089
t(time delay)	Control	.22	1.13	1.72	b7.14
Motion					
	4.283	2.854	3.277	4.992	5.219
	3.400	3.615	3.746	5.142	5.822
	3.212	3.772	4.074	4.650	3.894
	3.373	3.229	3.839	4.122	4.413
	2.888	3.298	4.952	3.543	3.284
	3.169	3.685	4.078	3.929	3.146
	3.005	3.116	3.300	3.447	3.520
	3.225	2.931	3.111	3.187	3.628
	3.187	3.233	4.950	2.996	3.991
	3.092	2.936	3.171	3.232	3.894
$\bar{\epsilon}_v$	3.284	3.267	3.850	3.924	4.081
σ	.383	.329	.681	.778	.853
t(time delay)	Control	.06	1.98	b2.24	b2.78
t(motion)	.35	.89	.87	.48	b2.61

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	96
ANOVA F	b4.01	b11.94	b2.72	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- Continued

(c) Horizontal error

rms horizontal error in meters for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	1.390	1.429	1.771	2.266	4.090
	1.777	1.462	1.787	1.861	3.759
	1.641	1.890	2.493	1.765	3.213
	.993	1.867	1.222	1.842	3.658
	.217	1.145	.839	1.296	2.229
	1.284	1.208	.914	1.626	1.760
	1.126	1.468	1.322	1.430	2.210
	.807	1.712	1.684	1.575	2.485
	1.133	1.336	1.446	2.025	3.150
	1.905	1.421	1.833	2.271	2.341
\bar{C}_h	1.277	1.494	1.531	1.796	2.890
σ	.401	.255	.491	.328	.789
t(time delay)	Control	.99	1.16	b2.37	b7.37
Motion					
	1.576	1.388	1.268	2.021	2.519
	1.225	1.596	1.005	2.550	2.237
	.788	1.162	2.140	2.787	2.015
	1.372	1.435	1.353	3.456	1.730
	.771	.913	1.720	1.663	1.310
	.782	2.090	1.437	1.178	1.696
	.950	1.006	1.113	1.121	1.447
	1.116	1.167	1.140	1.154	1.035
	.917	1.207	1.279	1.515	1.122
	.958	.786	1.874	1.085	1.556
\bar{C}_h	1.046	1.275	1.443	1.853	1.667
σ	.273	.377	.362	.828	.479
t(time delay)	Control	1.02	1.77	b3.59	b2.76
t(motion)	1.51	1.52	.46	.21	b4.19

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	b11.80	b15.41	b5.22	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- Continued

(d) Aileron deflection

rms aileron deflection ($\times 10^2$), rad, for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	1.901	1.951	3.466	3.834	4.409
	1.615	1.505	2.338	3.970	5.539
	1.748	1.987	2.211	2.343	4.076
	2.391	1.660	2.200	2.749	4.695
	1.814	1.270	2.426	2.576	3.947
	2.645	2.602	2.313	4.316	6.056
	1.376	2.254	2.564	2.921	4.968
	2.075	2.940	1.930	2.677	4.811
	1.878	1.919	2.283	2.719	4.370
	2.429	2.289	2.368	3.372	4.213
$\frac{\delta a}{\sigma}$	1.987	2.038	2.410	3.148	4.708
t(time delay)	.397	.504	.406	.680	.668
	Control	.21	1.73	b4.76	b11.17
Motion					
	1.298	1.922	1.529	1.969	2.439
	1.112	2.370	1.891	2.518	2.431
	1.245	1.836	1.773	2.738	1.637
	1.284	1.071	1.596	1.867	2.034
	1.494	1.009	1.650	1.473	1.913
	.794	1.231	1.187	1.181	1.886
	.903	1.607	2.049	2.083	1.487
	.808	1.153	1.345	1.319	1.742
	.906	.958	1.588	1.655	1.527
	1.087	1.094	1.190	1.181	1.458
$\frac{\delta a}{\sigma}$	1.093	1.425	1.580	1.808	1.855
t(time delay)	.237	.481	.283	.543	.361
t(motion)	Control	1.87	b2.74	b4.02	b4.28
	b6.12	b2.78	b5.30	b4.87	b71.81

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	b187.30	b42.73	b17.97	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- Continued

(e) Elevator deflection

rms elevator deflection ($\times 10^2$), rad, for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.710	0.941	1.258	1.291	1.564
	.538	.562	.794	1.227	1.532
	.700	.507	.683	.876	1.389
	.877	.670	.712	.993	1.126
	.716	.473	.891	.974	1.445
	.831	.908	.845	1.401	2.008
	.651	.879	.748	1.158	1.350
	.720	.728	.673	.788	1.514
	.667	.559	.819	.974	1.614
	.732	.644	.684	.844	1.460
$\frac{\delta e}{\sigma}$	0.714	0.687	0.811	1.049	1.500
σ	.093	.171	.174	.209	.225
t(time delay)	Control	.34	1.20	b4.15	b9.75
Motion					
	0.561	0.446	0.445	0.529	0.715
	.439	.843	.689	.894	.798
	.502	.711	.667	1.159	.594
	.552	.454	.534	.828	.606
	.598	.384	.652	.632	.680
	.403	.481	.560	.521	.696
	.377	.668	.698	.616	.690
	.396	.586	.585	.685	.736
	.355	.402	.560	.656	.573
	.512	.494	.498	.472	.543
$\frac{\delta e}{\sigma}$	0.469	0.547	0.589	0.699	0.663
σ	.086	.151	.085	.209	.081
t(time delay)	Control	1.31	2.01	b3.88	b3.33
t(motion)	b6.10	1.94	b3.62	b3.75	b11.07

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	b128.64	b33.60	b15.41	---
F _{critical}	1.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- Continued

(f) Audio task tracking error

rms audio task tracking error, volts (460 Hz/volt), for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.666	0.991	0.855	0.951	0.961
	.892	.626	.884	.827	.896
	.772	.691	.752	.578	.860
	.770	.758	.779	.653	.790
	.692	.522	.514	.527	.654
	.583	.480	.452	.544	.765
	.501	.417	.549	.438	.479
	.257	.474	.565	.414	.415
	.381	.361	.403	.505	.572
	.448	.359	.361	.375	.545
$\frac{\bar{B}}{\bar{\sigma}}$ t(time delay)	0.596 .199 Control	0.568 .200 -----	0.611 .191 -----	0.581 .184 -----	0.694 .188 -----
Motion					
	0.356	0.368	0.474	0.562	0.580
	.350	.378	.320	.434	.436
	.360	.270	.363	.463	.250
	.654	.327	.408	.464	.509
	.542	.321	.391	.421	.310
	.329	.346	.351	.277	.346
	.323	.469	.709	.236	.397
	.333	.298	.350	.220	.394
	.327	.453	.331	.333	.324
	.519	.273	.333	.335	.376
$\frac{\bar{B}}{\bar{\sigma}}$ t(time delay) t(motion)	0.409 .118 Control b _{6.46}	0.350 .069 ----- b _{3.25}	0.403 .117 ----- b _{2.94}	0.375 .112 ----- b _{3.04}	0.392 .097 ----- b _{4.52}

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOV F	b _{52.60}	0.85	0.42	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- Continued

(g) Audio task thumb-wheel deflection

rms audio task thumb-wheel deflection, volts (22.9 deg/volt), for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.543	0.721	0.776	0.692	0.841
	.578	.651	.607	.582	.640
	.542	.566	.668	.586	.419
	.612	.630	.598	.746	.686
	.541	.465	.474	.452	.790
	.617	.472	.400	.501	.543
	.455	.332	.384	.413	.613
	.334	.418	.502	.480	.411
	.317	.313	.287	.420	.427
	.388	.353	.469	.453	.521
$\frac{\bar{\delta}_s}{\sigma}$	0.493	0.492	0.516	0.532	0.589
t(time delay)	.112	.144	.147	.115	.153
Control		-----	-----	-----	-----
Motion					
	0.317	0.395	0.418	0.510	0.437
	.374	.468	.468	.420	.463
	.299	.386	.380	.316	.254
	.559	.279	.361	.407	.382
	.386	.386	.337	.391	.323
	.394	.321	.306	.285	.286
	.317	.418	.551	.282	.333
	.416	.239	.369	.302	.399
	.327	.402	.309	.408	.327
	.510	.253	.248	.354	.331
$\frac{\bar{\delta}_s}{\sigma}$	0.390	0.355	0.375	0.368	0.354
t(time delay)	.086	.077	.087	.073	.066
t(motion)	Control	-----	-----	-----	-----
	b2.30	b2.66	b2.63	b3.81	b4.48

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	b50.15	0.49	1.00	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- Continued

(h) Audio task thumb-wheel input frequency

rms audio task thumb-wheel input frequency, Hz, for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.54	0.76	0.51	0.65	0.50
	.55	.54	.59	.59	.60
	.55	.54	.56	.83	.55
	.46	.60	.60	.61	.62
	.54	.53	.36	.47	.39
	.72	.45	.43	.54	.43
	.64	.55	.42	.54	.50
	.55	.53	.38	.49	.61
	.60	.45	.66	.54	.48
	.63	.59	.57	.57	.58
$\bar{\omega}_{\delta}$	0.58	0.56	0.51	0.58	0.53
$\bar{\sigma}$	.07	.09	.10	.10	.08
t(time delay)	Control	----	----	----	----
Motion					
	0.46	0.54	0.69	0.55	0.68
	.69	.56	.62	.41	.39
	.34	.56	.55	.38	.48
	.69	.58	.34	.65	.64
	.48	.74	.55	.68	.48
	.69	.54	.38	.50	.58
	.59	.57	.54	.65	.63
	.66	.41	.63	.71	.53
	.54	.61	.57	.56	.52
	.73	.48	.64	.57	.51
$\bar{\omega}_{\delta}$	0.59	0.56	0.55	0.57	0.54
$\bar{\sigma}$	.13	.09	.11	.11	.09
t(time delay)	Control	----	----	----	----
t(motion)	-----	----	----	----	----

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOVA F	1.04	1.04	b2.60	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE IV.- Concluded

(i) Pilot gain, K_p

rms pilot gain, K_p , for units of time delay ^a of -					
	0	4	8	12	16
No motion					
	0.815	0.728	0.908	0.728	0.875
	.648	1.039	.686	.703	.714
	.702	.819	.888	1.015	.766
	.795	.831	.768	1.141	1.000
	.783	.891	.922	.858	.830
	1.060	.982	.885	.921	.801
	.908	.797	.699	.944	.860
	1.296	.883	.889	1.161	1.027
	.832	.867	.712	.831	.910
	.866	.982	1.300	1.208	.768
$\frac{K_p}{\sigma}$	0.871	0.882	0.866	0.951	0.855
t(time delay)	.187	.096	.179	.178	.102
Control	-----	-----	-----	-----	-----
Motion					
	0.890	1.073	0.882	0.907	0.753
	1.070	1.239	1.463	.969	1.062
	.831	1.044	1.047	.684	1.014
	.855	.854	.883	.878	.751
	.713	1.205	.861	.929	1.042
	1.199	.927	.872	1.027	.826
	.982	.892	.778	1.199	.840
	1.249	.801	1.056	1.375	1.015
	1.000	.887	.884	1.224	1.011
	.983	.926	.745	1.056	.880
$\frac{K_p}{\sigma}$	0.977	0.985	0.947	1.025	0.919
t(time delay)	.165	.149	.206	.199	.122
Control	-----	-----	-----	-----	-----
t(motion)	1.353	1.836	0.943	0.873	1.279

	Motion	Delay	Motion/delay interaction	Error
d.o.f.	1	4	4	90
ANOV F	^b 6.943	1.094	0.075	---
F _{critical}	3.96	2.49	2.49	

^aEach unit of time delay equals 31.25 msec.^bSignificant difference at 5-percent level.

TABLE V.- MEAN VALUES FOR SIDE-TASK-ONLY PARAMETERS

Subject	λ	Pulse width	Data points	Session	$\bar{\delta}_s$	\bar{B}	\bar{K}_*
A	1.0	0.50	3	Early	0.3293	0.2602	1.3520
A	2.0	.25	10	Early	1.1815	.5582	2.1820
A	2.5	.25	3	Early	2.3740	.9813	2.4394
A	1.0	.25	3	Late	.2243	.1640	1.4052
A	2.0	.25	3	Late	.5248	.2134	2.4852
A	3.0	.25	3	Late	2.0699	.6260	3.3216
A	4.0	.25	1	Late	4.3093	1.1993	3.5932
C	.5	.50	4	Early	.4917	.7064	.6972

TABLE VI.- COMPARISON OF SIDE TASK ONLY, PRIMARY TASK ONLY, AND COMBINED TASK

EXPERIMENTAL RESULTS FOR SUBJECT A WITH INSTABILITY λ OF 2.0;FIXED BASE WITH $\tau_v = 0$

Performance parameters	Experimental results for -		
	Side task only, 8 replicates	Primary task only, ^a 10 replicates	Combined task, 10 replicates
c_v :			
Mean . . .		2.8344	2.9056
σ . . . .		.1024	.1216
t			1.4160
c_h :			
Mean . . .		.7049	.7440
σ . . . .		.2552	.1241
t . . . .			.4355
$c_v + c_h$:			
Mean . . .		3.5396	3.6372
σ . . . .		.3446	.1988
t . . . .			.7757
$\delta_a \times 10^2$:			
Mean . . .		1.2989	1.3184
σ . . . .		.1587	.3498
t . . . .			.1607
$\delta_e \times 10^2$:			
Mean . . .		.4133	.3746
σ . . . .		.0702	.0819
t			1.0778
$\eta \times 10^2$:			
Mean . . .		.4856	.5173
σ . . . .		.1724	.0963
t . . . .			.5065
$\xi \times 10^2$:			
Mean . . .		.5675	.4392
σ . . . .		.2029	.0702
t			1.8899
Tone B:			
Mean . . .	0.2439		.4179
σ . . . .	.0413		.1606
t			^b 2.9689
δ_B :			
Mean . . .	.6676		1.0428
σ . . . .	.1391		.2999
t			^b 3.2540
Pilot gain, K_a :			
Mean . . .	2.7298		2.5877
σ . . . .	.2494		.3692
t . . . .			.9294

^aData obtained motion-base conditions (assumption is that fixed-base and motion-base results are the same for primary task only).^bSignificant difference at 1-percent level.

TABLE VII.- COMPARISON OF SIDE TASK ONLY, PRIMARY TASK ONLY, AND COMBINED TASK

EXPERIMENTAL RESULTS FOR SUBJECT A WITH INSTABILITY λ OF 2.0;MOTION BASE WITH $\tau_v = \tau_m = 0$

Performance parameters	Experimental results for -		
	Side task only, ^a 8 replicates	Primary task only, 10 replicates	Combined task, 10 replicates
C_v :			
Mean . . .		2.8344	2.8406
σ . . . .		.1024	.1296
t . . . .			.1175
C_h :			
Mean . . .		.7049	.5939
σ . . . .		.2552	.0920
t			1.2938
$C_v + C_h$:			
Mean . . .		3.5396	3.4345
σ . . . .		.3446	.1688
t . . . .			.8666
$\delta_a \times 10^2$:			
Mean . . .		1.2989	1.2191
σ . . . .		.1587	.2093
t . . . .			.9608
$\delta_e \times 10^2$:			
Mean . . .		.4113	.3969
σ . . . .		.0703	.0582
t . . . .			.5007
$\eta \times 10^2$:			
Mean . . .		.4856	.4109
σ . . . .		.1724	.1088
t			1.1591
$\zeta \times 10^2$:			
Mean . . .		.5675	.3929
σ . . . .		.2029	.0783
t			^b 2.5390
Tone B:			
Mean . . .	0.2439		.4143
σ . . . .	.0413		.1342
t			^c 3.4438
δ_B :			
Mean . . .	.6676		1.0517
σ . . . .	.1391		.2581
t			^c 3.7779
Pilot gain, K_{pi} :			
Mean . . .	2.7298		2.6102
σ . . . .	.2494		.3166
t . . . .			.8720

^aData obtained fixed base.^bSignificant difference at 5-percent level.^cSignificant difference at 1-percent level.

TABLE VIII.- COMPARISON OF SIDE TASK ONLY, PRIMARY TASK ONLY, AND COMBINED TASK

EXPERIMENTAL RESULTS FOR SUBJECT C WITH INSTABILITY λ OF 0.5;FIXED BASE WITH $\tau_v = 0$

Performance parameters	Experimental results for -		
	Side task only, 4 replicates	Primary task only, ^a 5 replicates	Combined task, 10 replicates
c_v :			
Mean . . .		3.0632	3.3407
σ . . . .		.0830	.3440
t			1.7471
c_h :			
Mean . . .		.8199	1.2772
σ . . . .		.1896	.4012
t			b2.3855
$c_v + c_h$:			
Mean . . .		3.8831	4.6178
σ . . . .		.2556	.6398
t			b2.4348
$\delta_a \times 10^2$:			
Mean . . .		1.0219	1.9872
σ . . . .		.1230	.3968
t			c5.2276
$\delta_e \times 10^2$:			
Mean . . .		.3302	.7142
σ . . . .		.0798	.0931
t			c7.8612
$\eta \times 10^2$:			
Mean . . .		.6045	.9871
σ . . . .		.0675	.2377
t			c3.4696
$\zeta \times 10^2$:			
Mean . . .		.4776	.8907
σ . . . .		.1100	.3139
t			b2.8116
Tone B:			
Mean . . .	0.7064		.5962
σ . . . .	.1641		.1987
t . . . .			.9772
δ_s :			
Mean . . .	.4917		.4927
σ . . . .	.1084		.1121
t . . . .			.0163
Pilot gain, K_s :			
Mean . . .	.6973		.8705
σ . . . .	.0185		.1869
t			1.8056

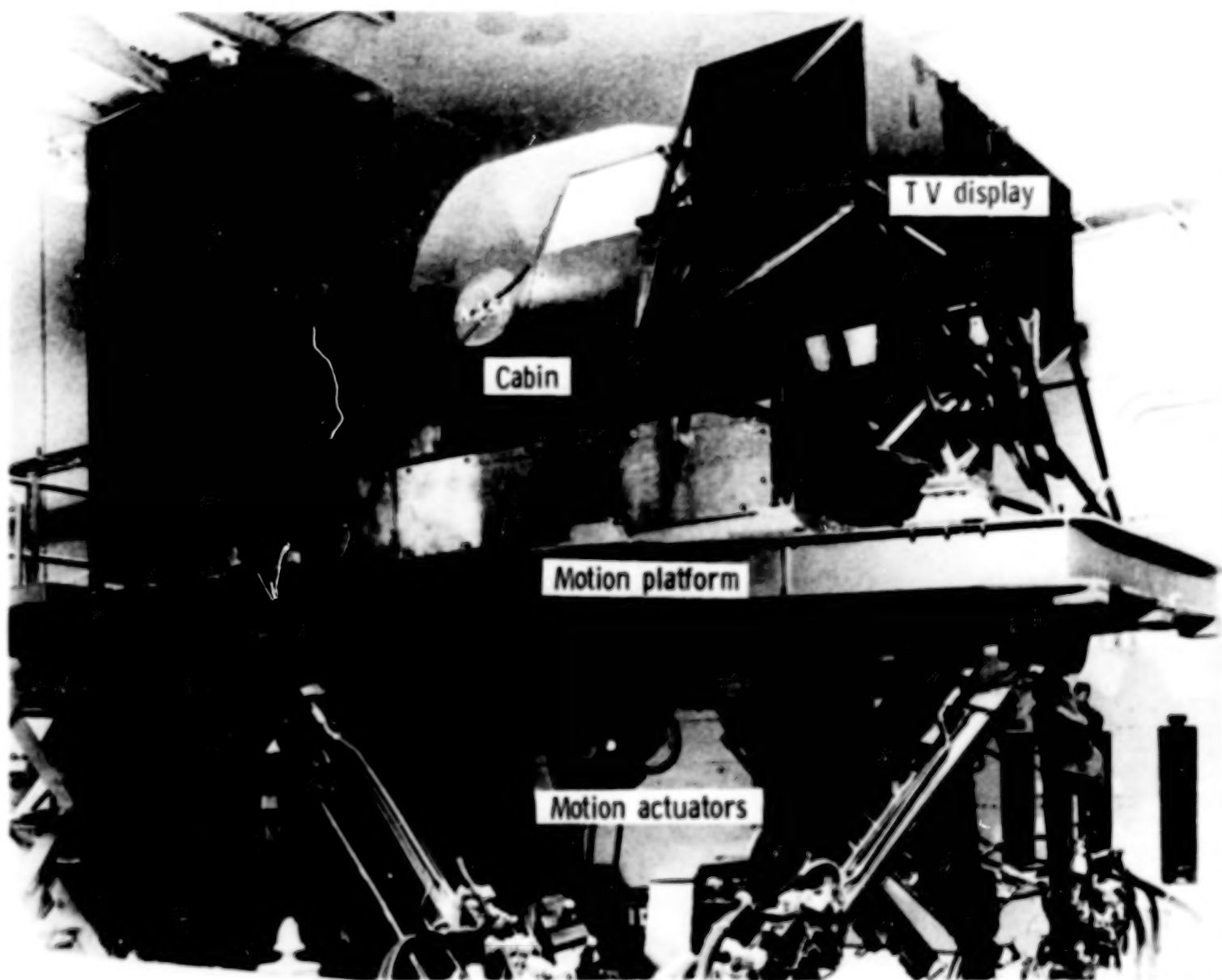
^aData obtained motion-base conditions (assumption is that fixed-base and motion-base results are the same for primary task only).^bSignificant difference at 5-percent level.^cSignificant difference at 1-percent level.

TABLE IX.- COMPARISON OF SIDE TASK ONLY, PRIMARY TASK ONLY, AND COMBINED TASK

EXPERIMENTAL RESULTS FOR SUBJECT C WITH INSTABILITY λ OF 0.5;MOTION BASE WITH $\tau_v = \tau_m = 0$

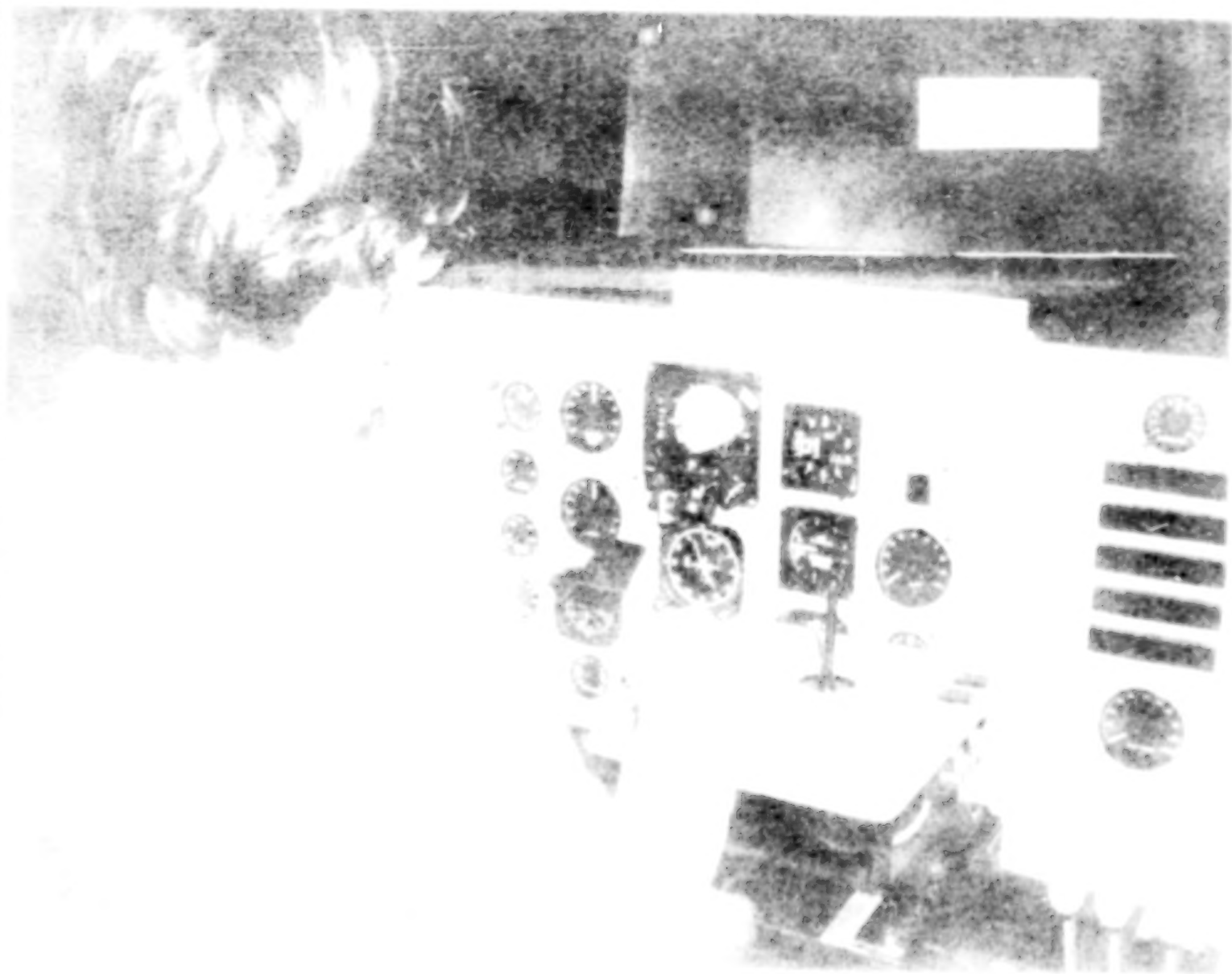
Performance parameters	Experimental results for -		
	Side task only, ^a 4 replicates	Primary task only, 5 replicates	Combined task, 10 replicates
c_v :			
Mean . . .		3.0632	3.2834
σ . . . .		.0830	.3836
t			1.2479
c_h :			
Mean . . .		.8199	1.0456
σ . . . .		.1896	.2727
t			1.6481
$c_v + c_h$:			
Mean . . .		3.8831	4.3356
σ . . . .		.2556	.6269
t			1.5282
$\delta_a \times 10^2$:			
Mean . . .		1.0219	1.0929
σ . . . .		.1230	.2368
t . . . .			.6222
$\delta_e \times 10^2$:			
Mean . . .		.3302	.4694
σ . . . .		.0798	.0863
t			^c 3.0140
$\eta \times 10^2$:			
Mean . . .		.6045	.9045
σ . . . .		.0675	.1943
t			^b 2.3834
$\xi \times 10^2$:			
Mean . . .		.4776	.7308
σ . . . .		.1100	.1321
t			^c 3.6772
Tone B:			
Mean . . .	0.7064		.4091
σ . . . .	.1641		.1176
t			^c 3.8418
δ_B :			
Mean . . .	.4917		.3899
σ . . . .	.1084		.0861
t			1.8648
Pilot gain, K_p :			
Mean . . .	.6973		.9772
σ . . . .	.0185		.1654
t			^c 3.2972

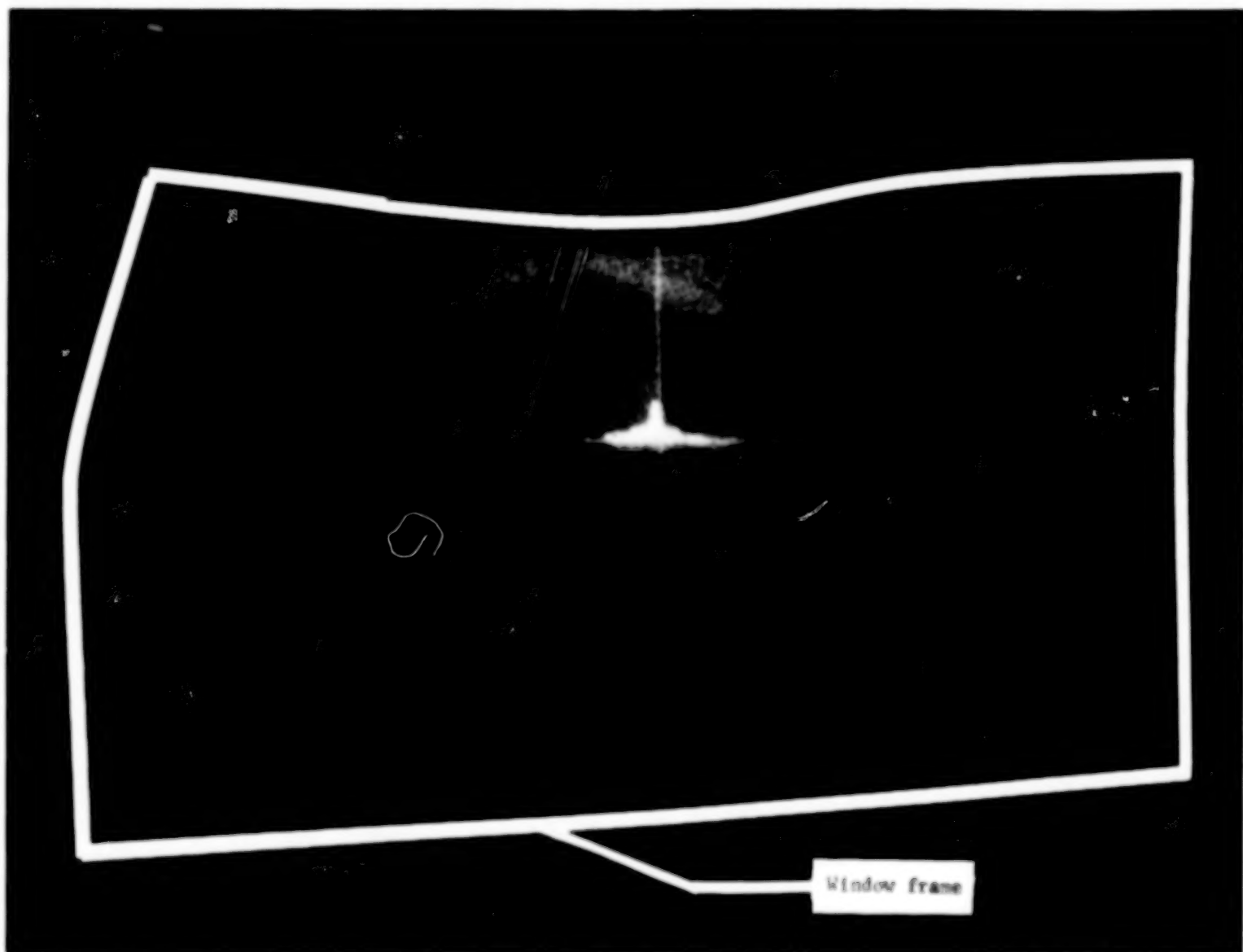
^aData obtained fixed base.^bSignificant difference at 5-percent level.^cSignificant difference at 1-percent level.



L-73-7163.1

Figure 1.- Langley six-degree-of-freedom vision-motion simulator.





L-75-3154.1

Figure 3.- Photograph of visual scene observed by subjects when tracker aircraft was nearly aligned with target.

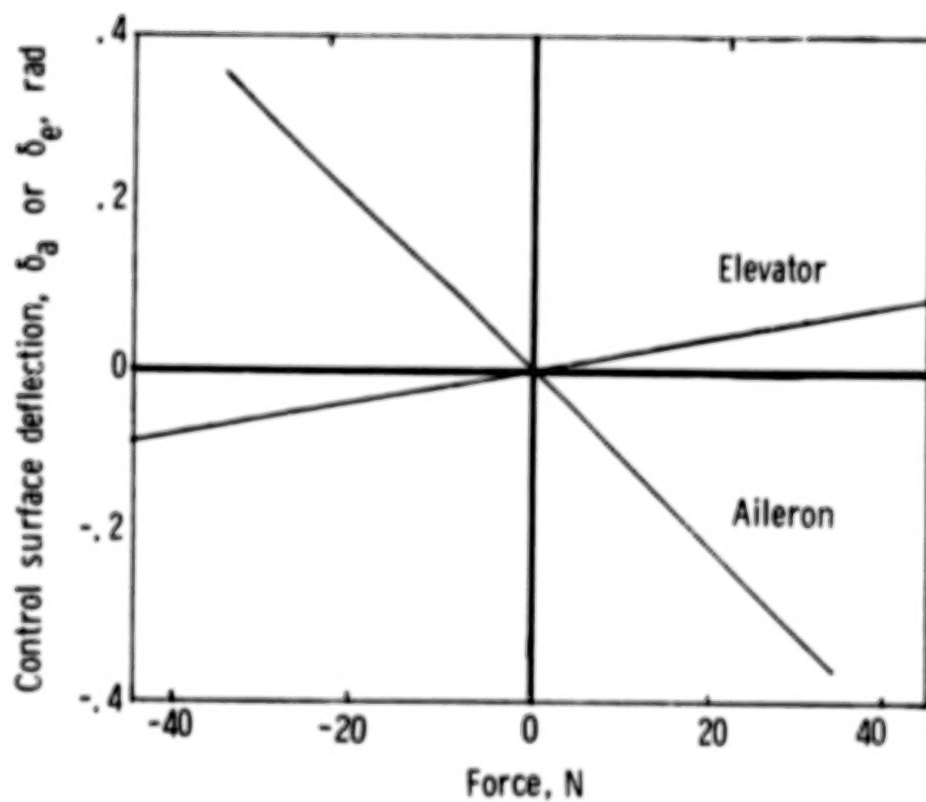
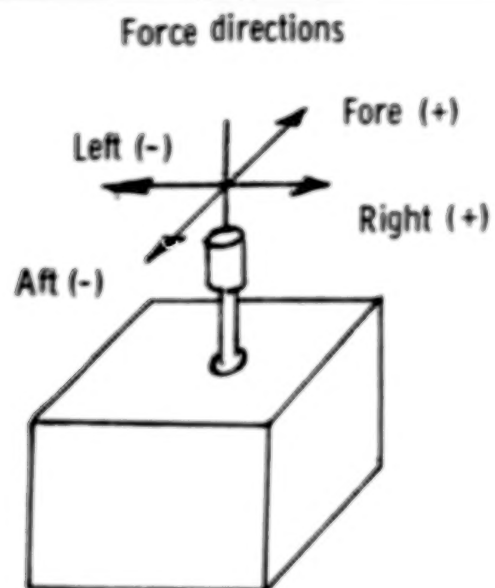


Figure 4.- Two-axis force-stick characteristics.

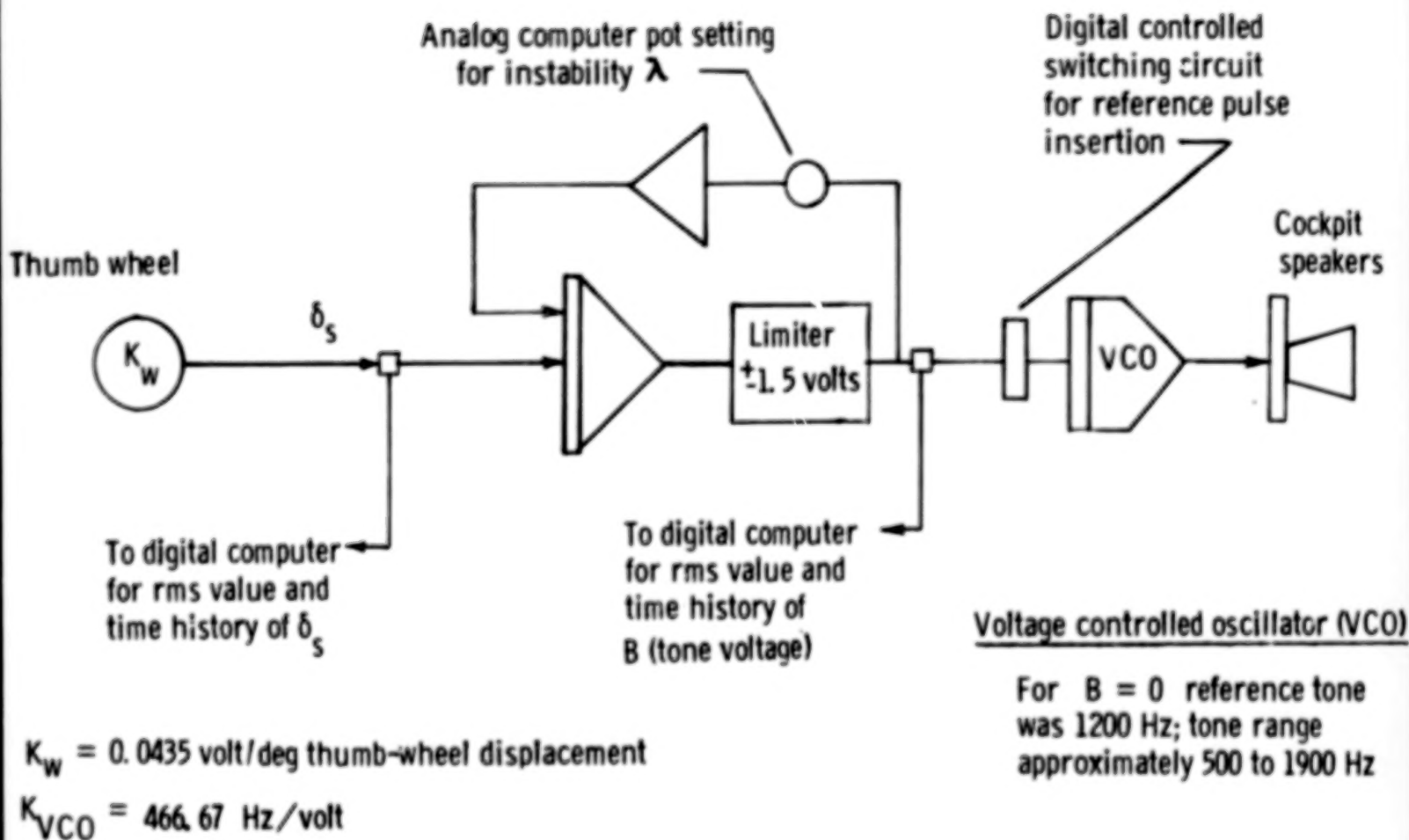


Figure 5.- Rudimentary sketch of audio side task.

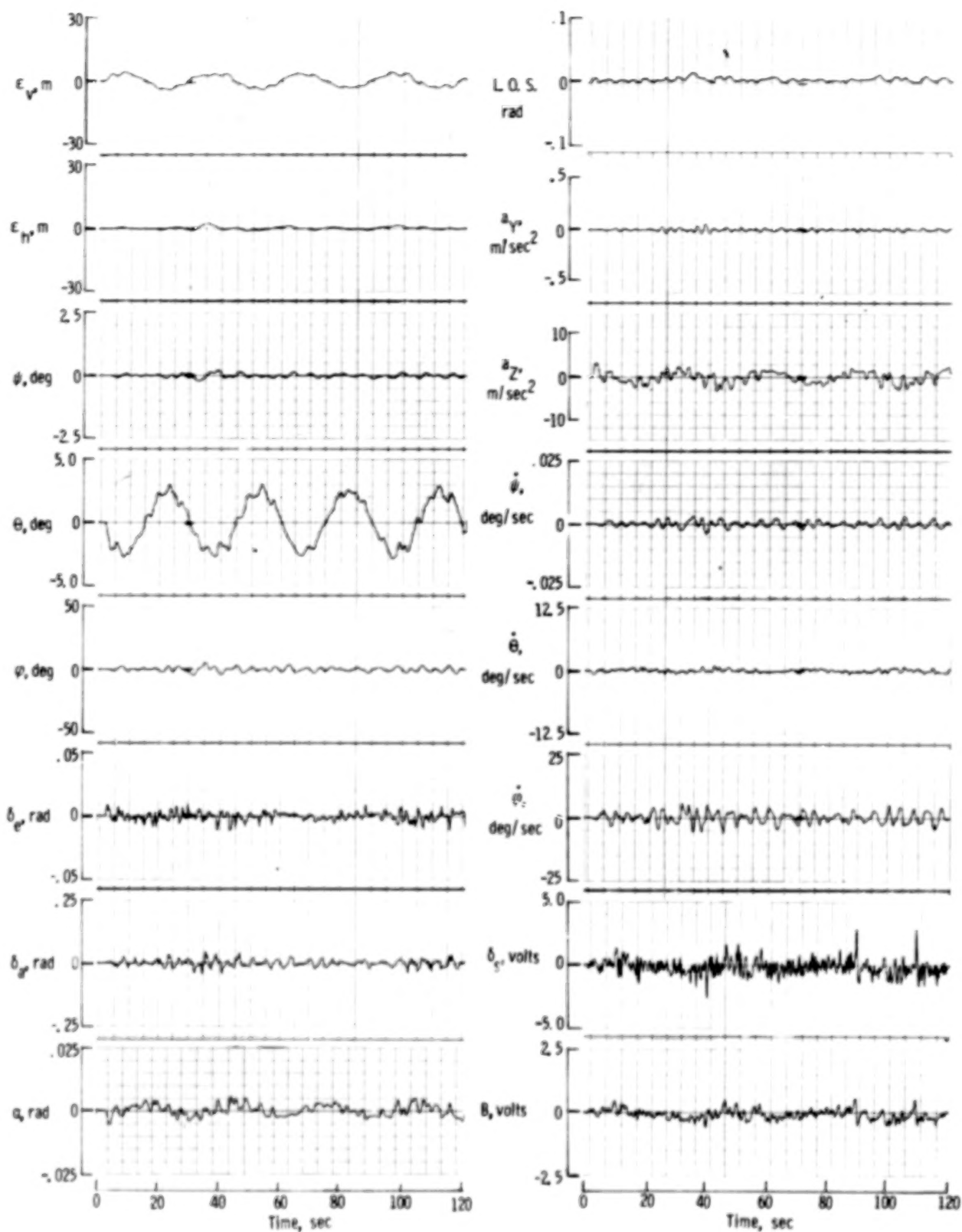


Figure 6.- Typical time history with no motion and 8 units of time delay; subject A.

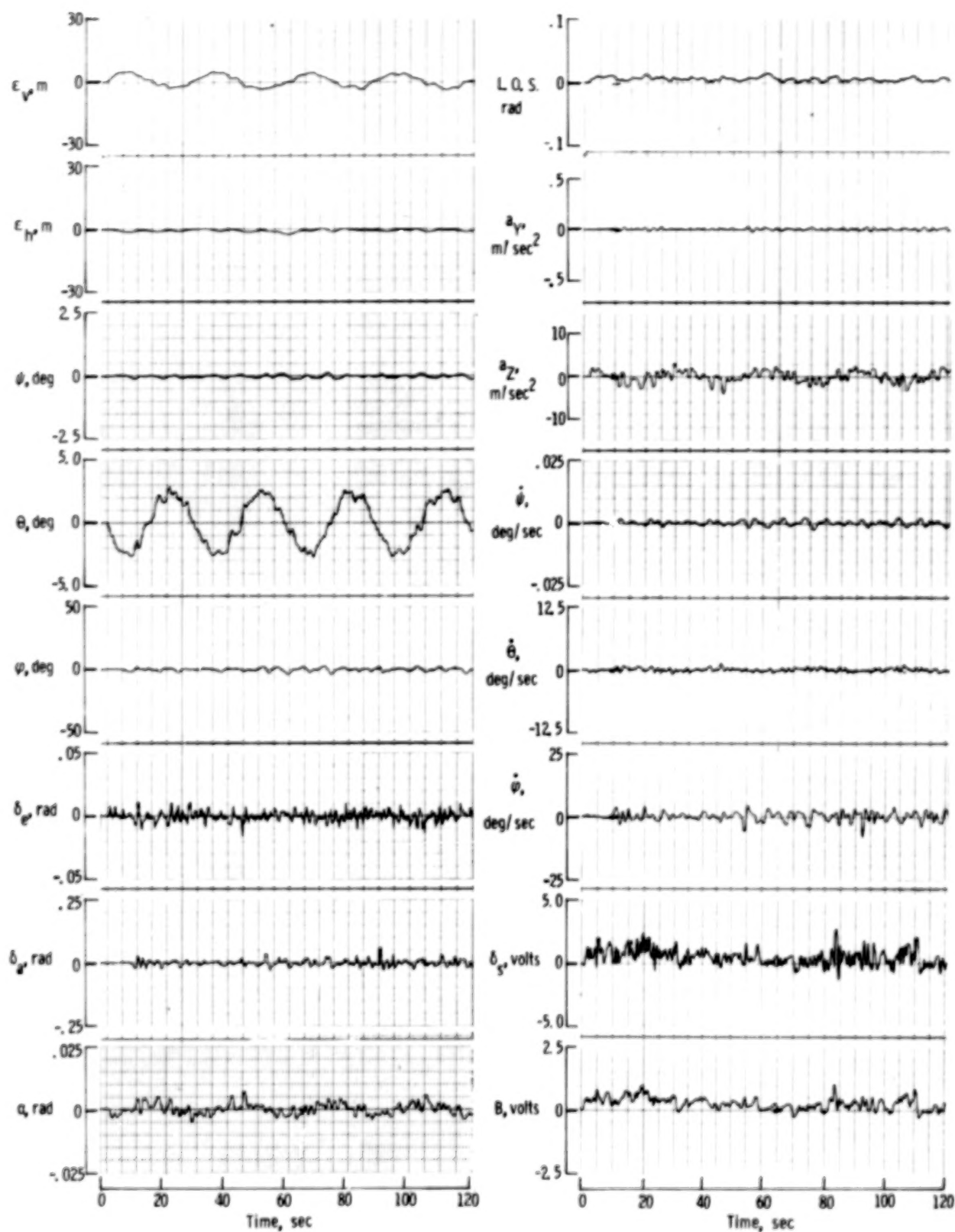


Figure 7.- Typical time history with motion and 8 units of time delay; subject A.

+ Computed flight data
— Base command

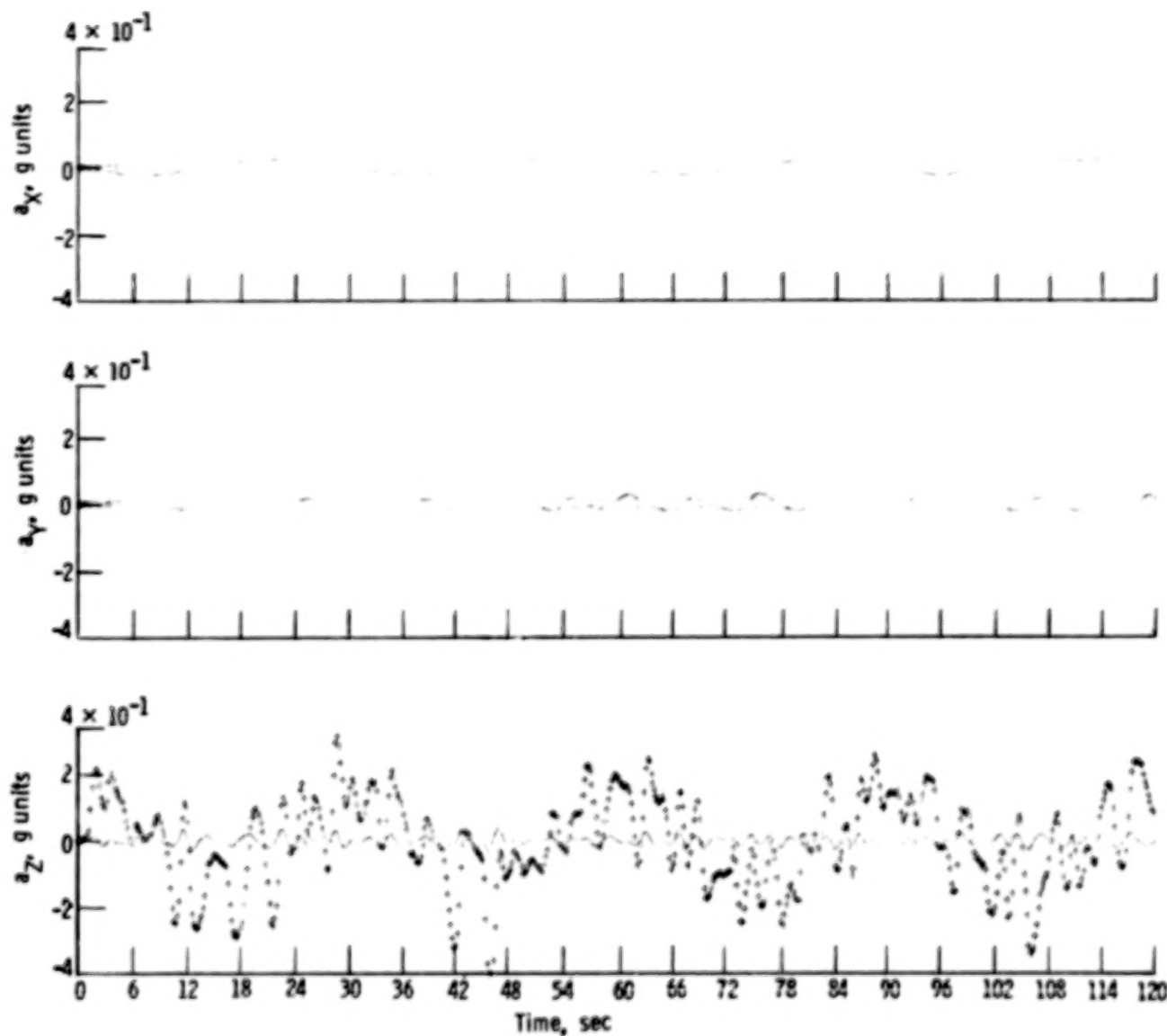


Figure 8.- Computed motion-base commands for typical time history (see fig. 7) with 8 units of time delay; subject A.

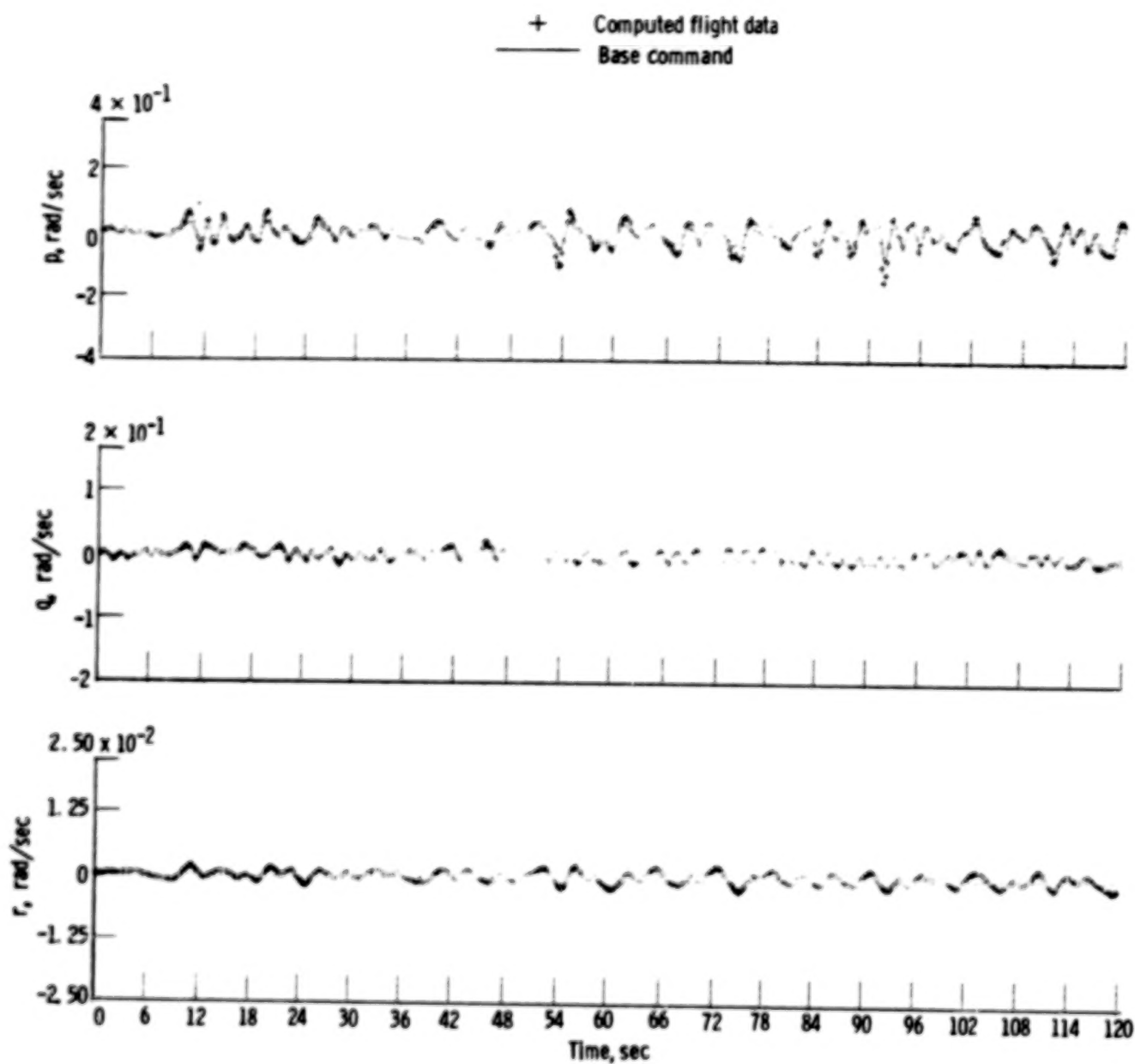
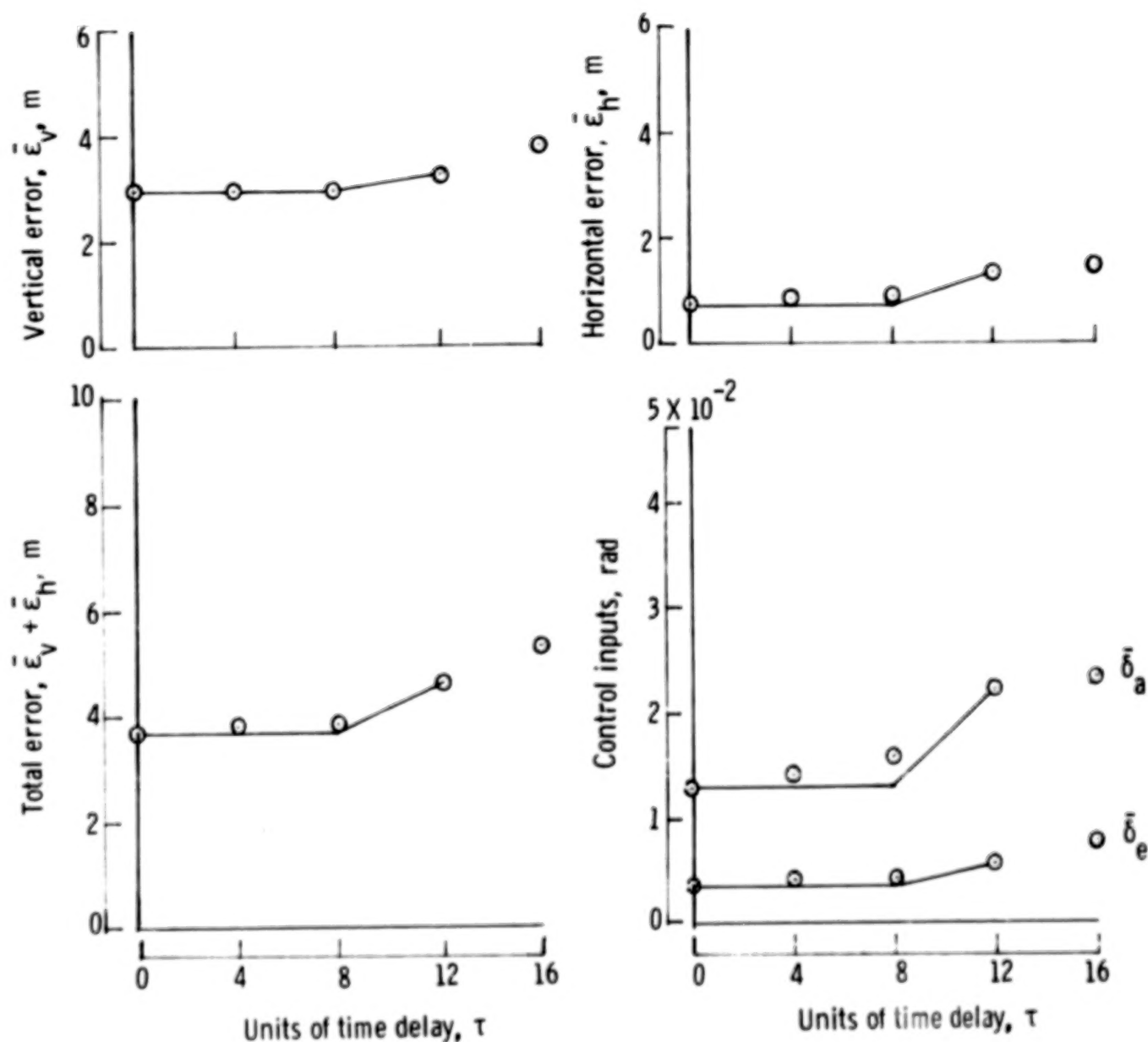
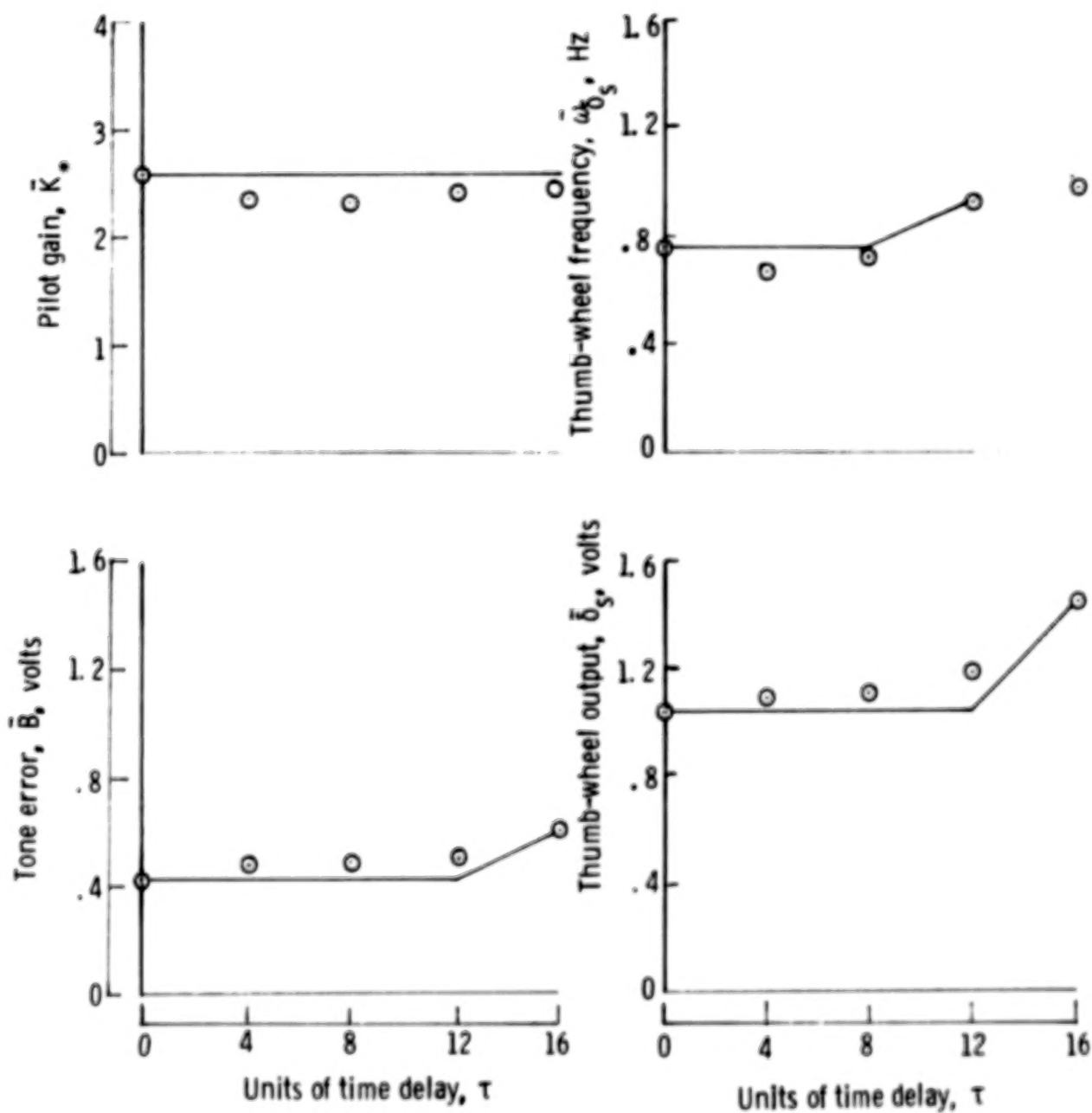


Figure 8.- Concluded.



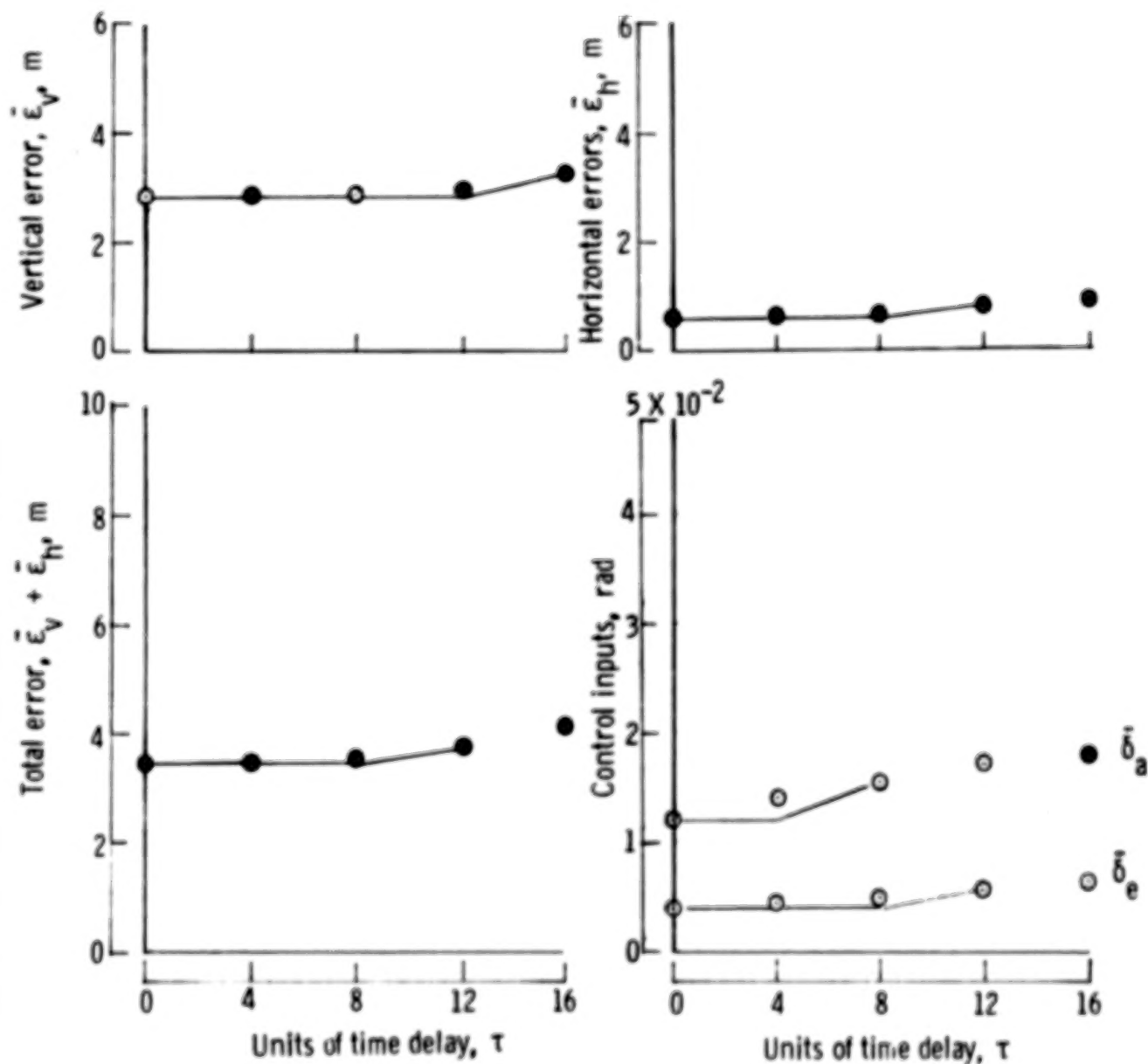
(a) Primary task parameters.

Figure 9.- Performance measures for subject A without motion. (Lines are used to denote statistical significance of time delays. One unit of time delay equals 31.25 msec.)



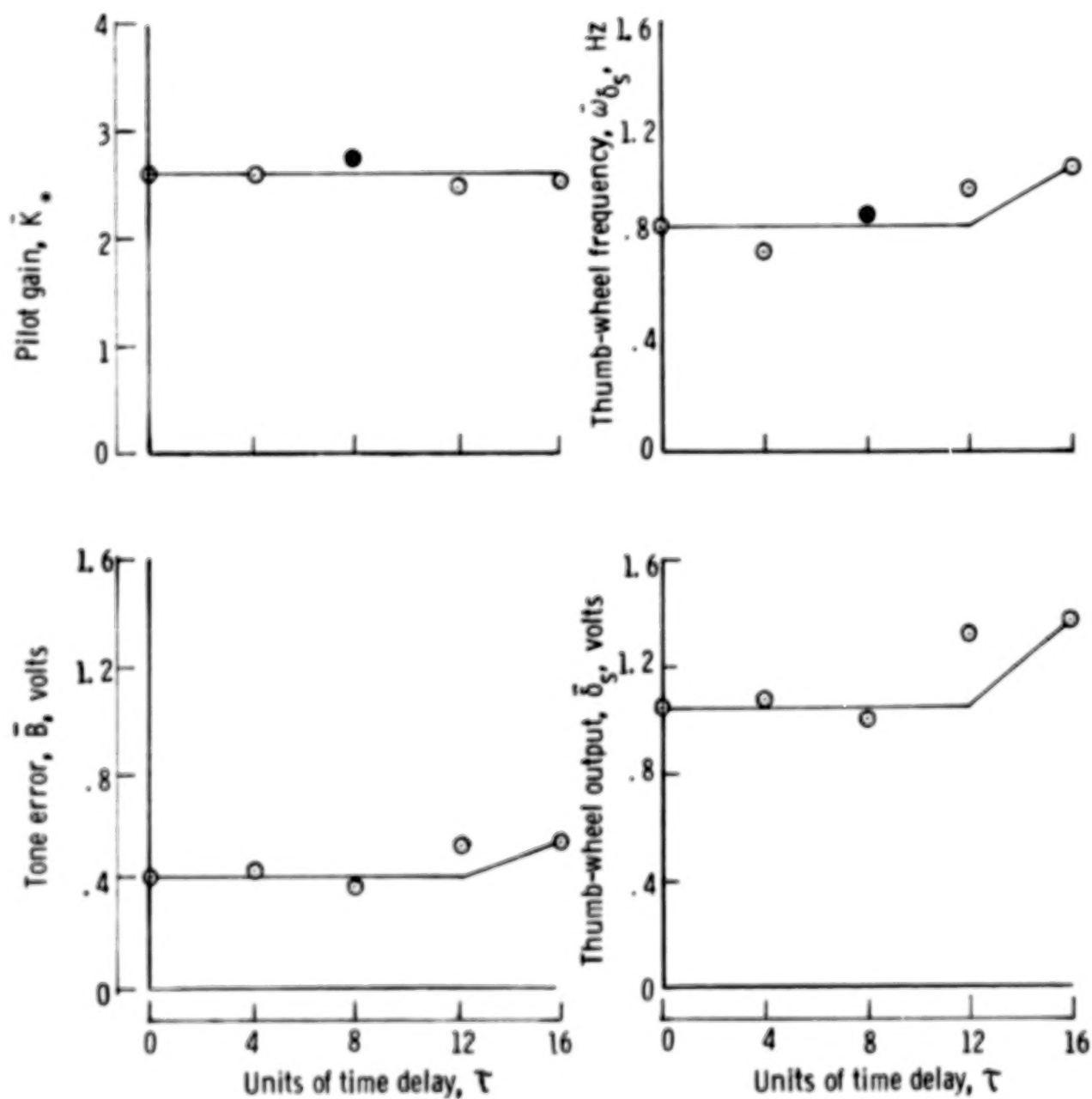
(b) Side task parameters.

Figure 9.- Concluded.



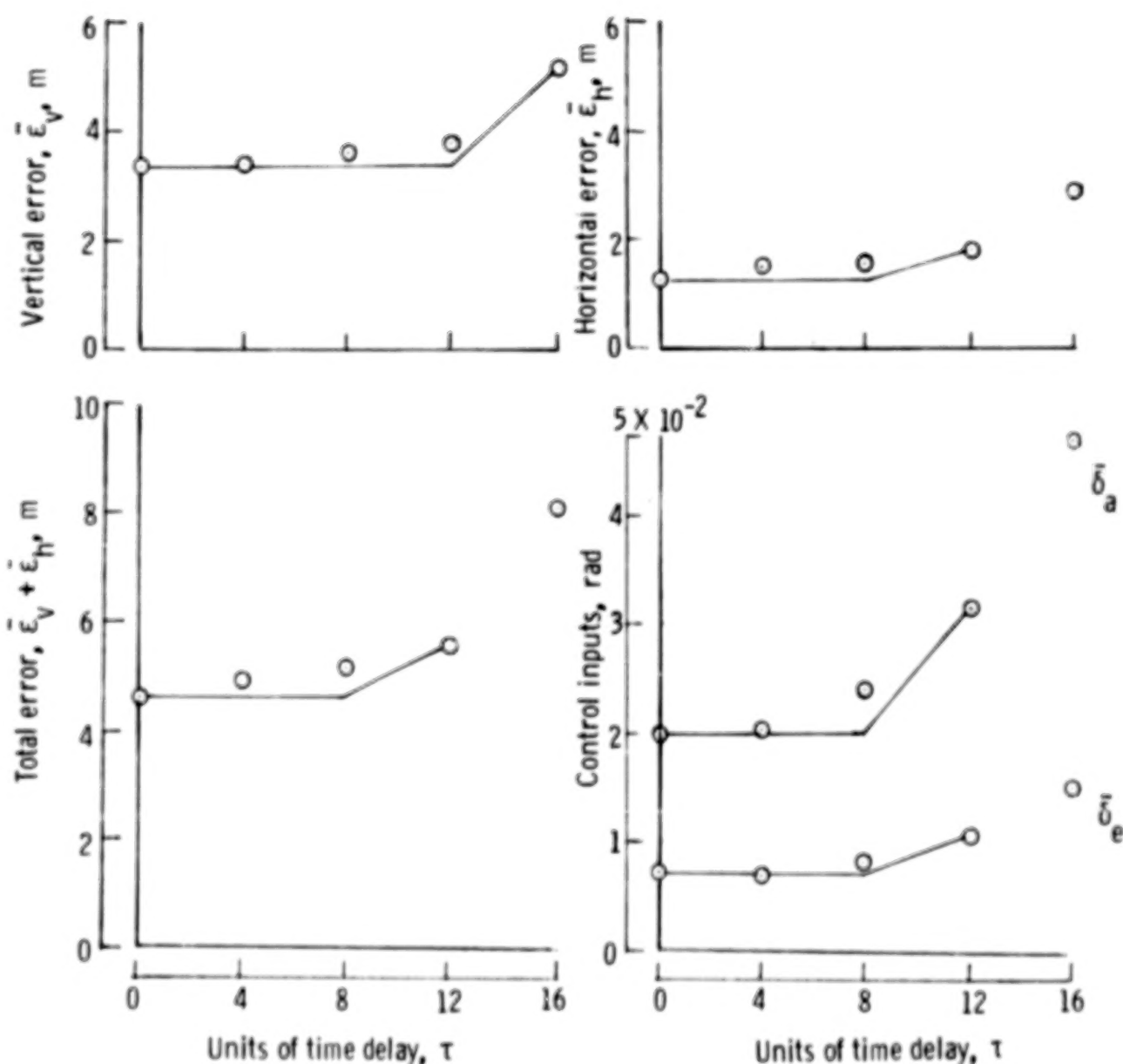
(a) Primary task variables.

Figure 10.- Performance measures for subject A with motion. (Lines and solid symbols are used to denote statistical significance of time delays and motion cues, respectively. One unit of time delay equals 31.25 msec.)



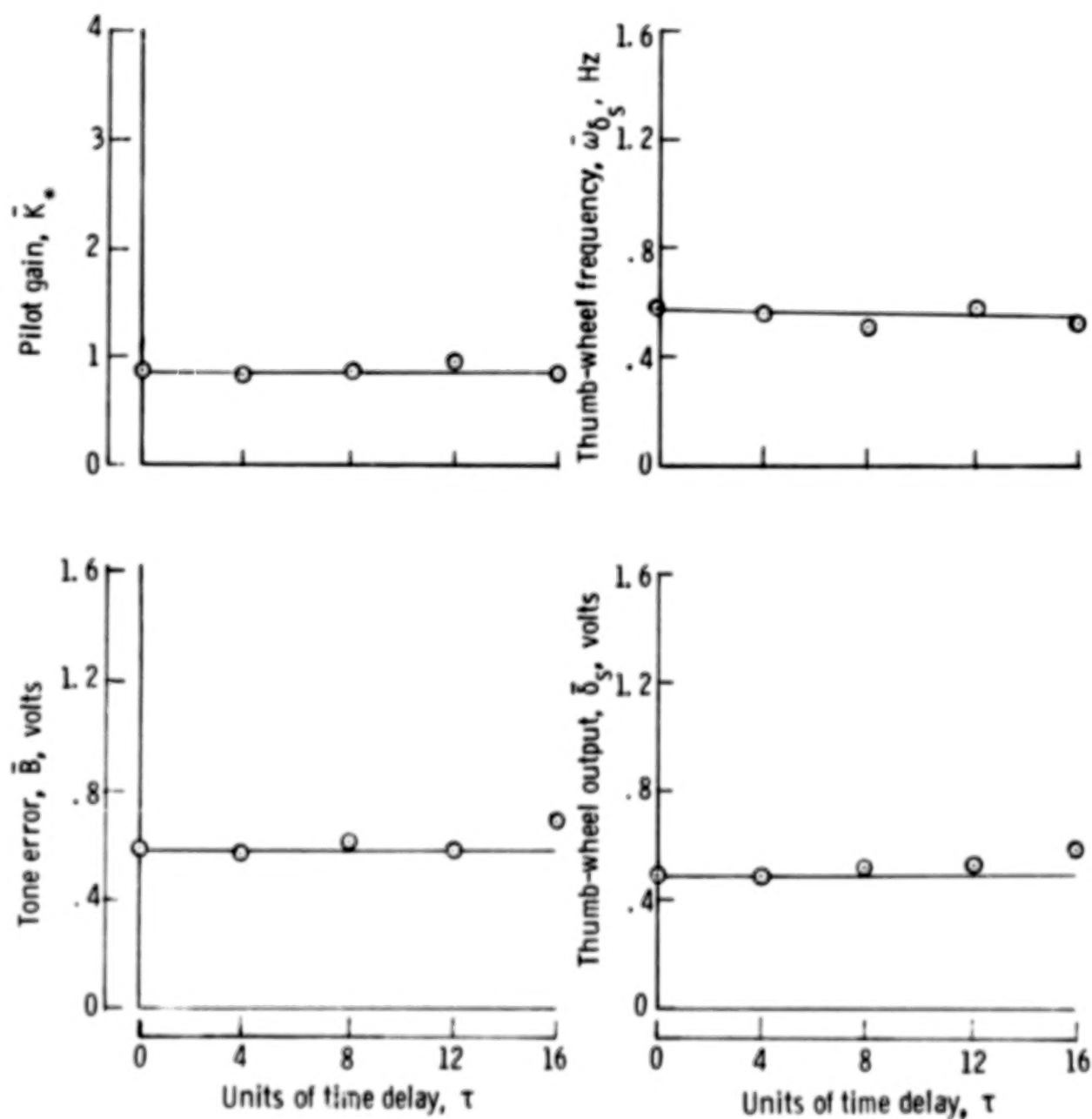
(b) Side task parameters.

Figure 10.- Concluded.



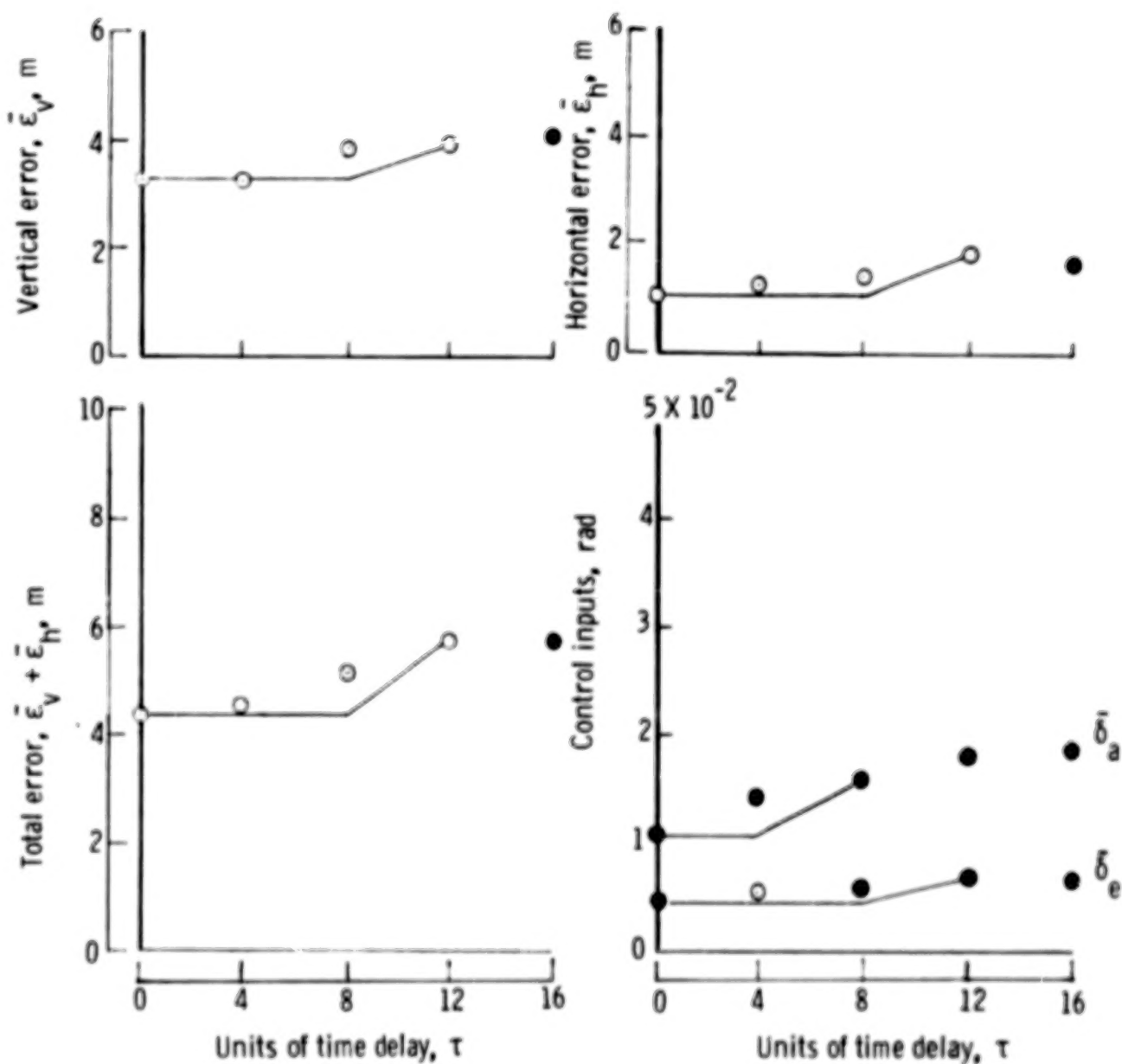
(a) Primary task parameters.

Figure 11.- Performance measures for subject C without motion. (Lines are used to denote statistical significance of time delays. One unit of time delay equals 31.25 msec.)



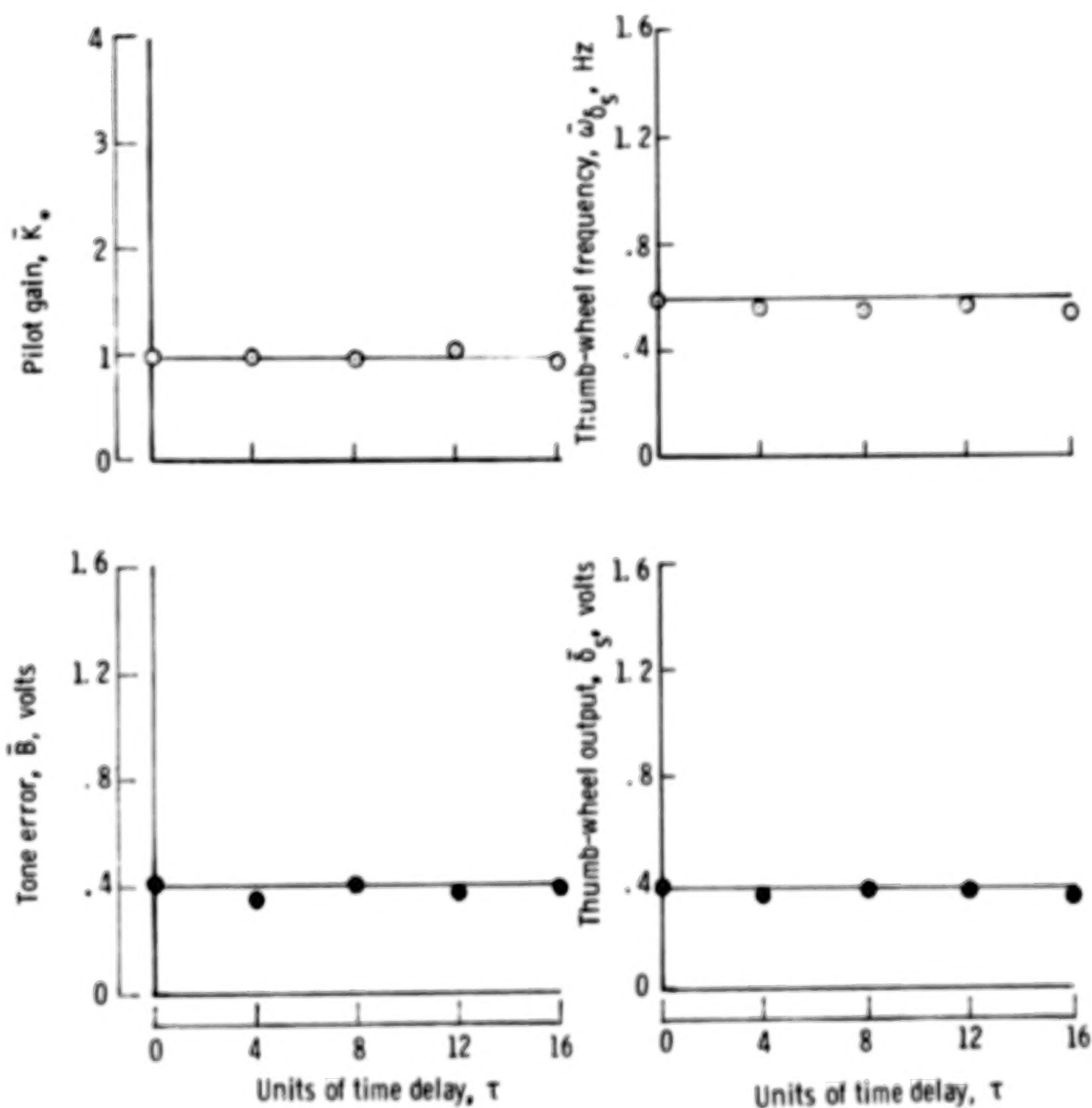
(b) Side task parameters.

Figure 11.- Concluded.



(a) Primary task parameters.

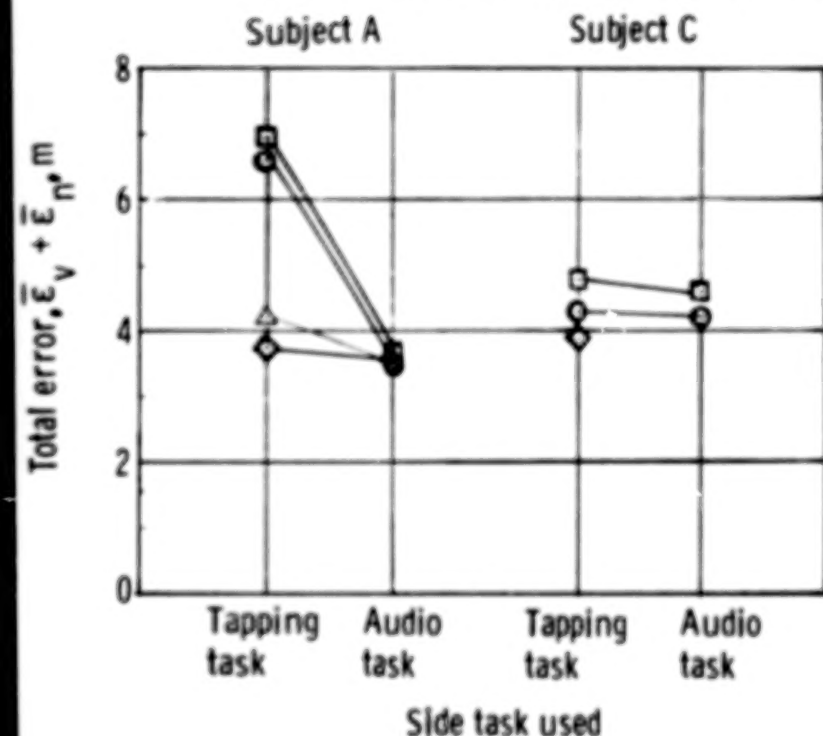
Figure 12.- Performance measures for subject C with motion. (Lines and solid symbols are used to denote statistical significance of time delays and motion cues, respectively. One unit of time delay equals 31.25 msec.)



(b) Side task parameters.

Figure 12.- Concluded.

- Full motion
- No motion
- ◇ Full motion with no side task
- △ Full motion with good lateral trim (subject A, tapping task only)



Subject	Tapping task (ref. 3)		Audio task	
	Fixed base	Motion base	Fixed base	Motion base
A	4	8	8	8
B	4	8	-	-
C	8	8	8	8
D	3	8	-	-

(a) Total tracking error at $\tau = 0$.

(b) Acceptable time delay values, τ_{accept} .

Figure 13.- Comparison of total tracking error and acceptable time delay values for different subjects using tapping and audio side tasks.

- Subject A, data from late sessions
- Subject A, data from early sessions
- ◇ Subject C
- Gain boundaries

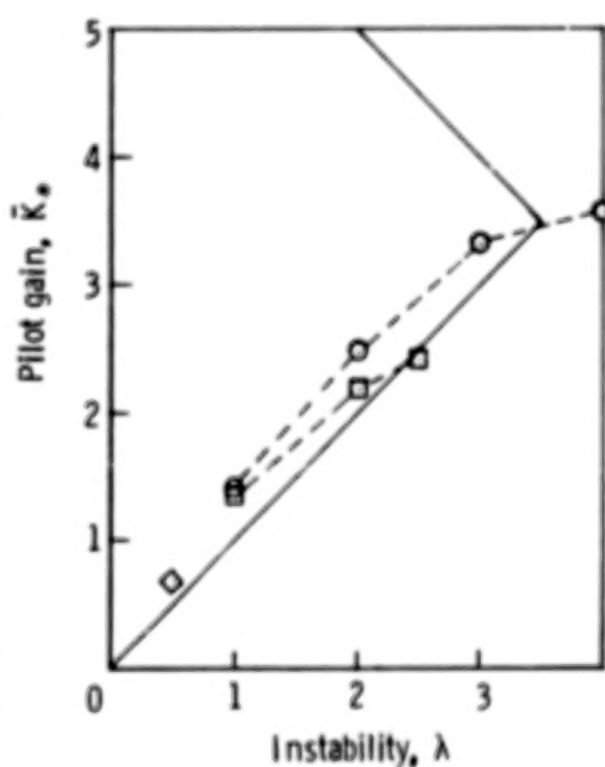
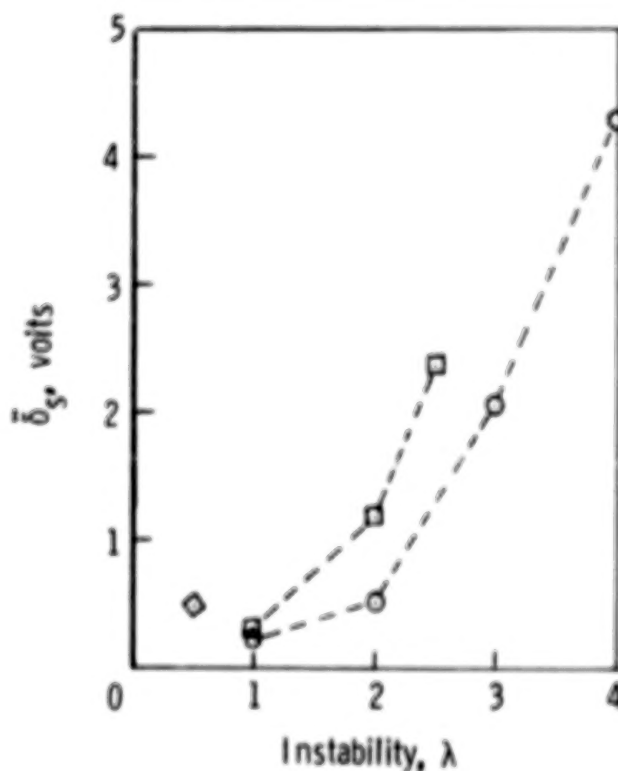
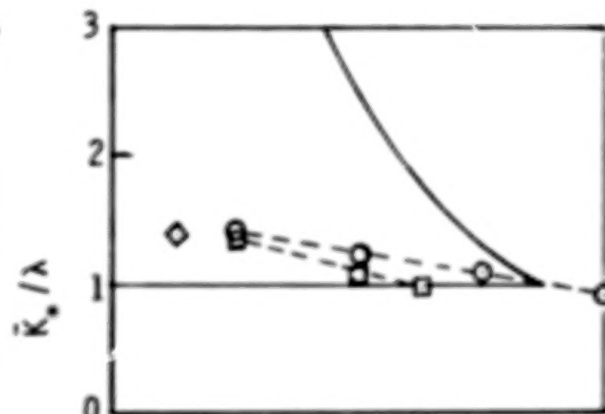
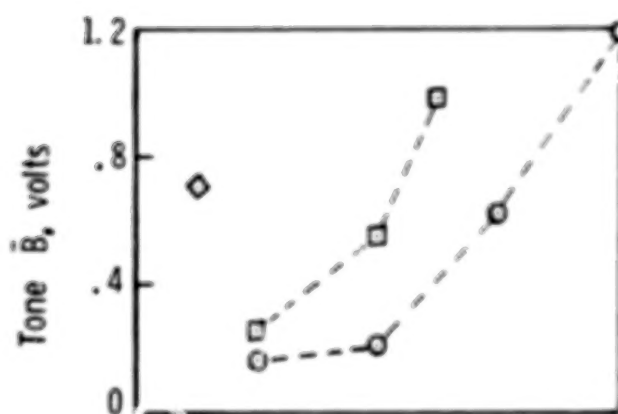


Figure 14.- Summary of data for side-task-only tests.

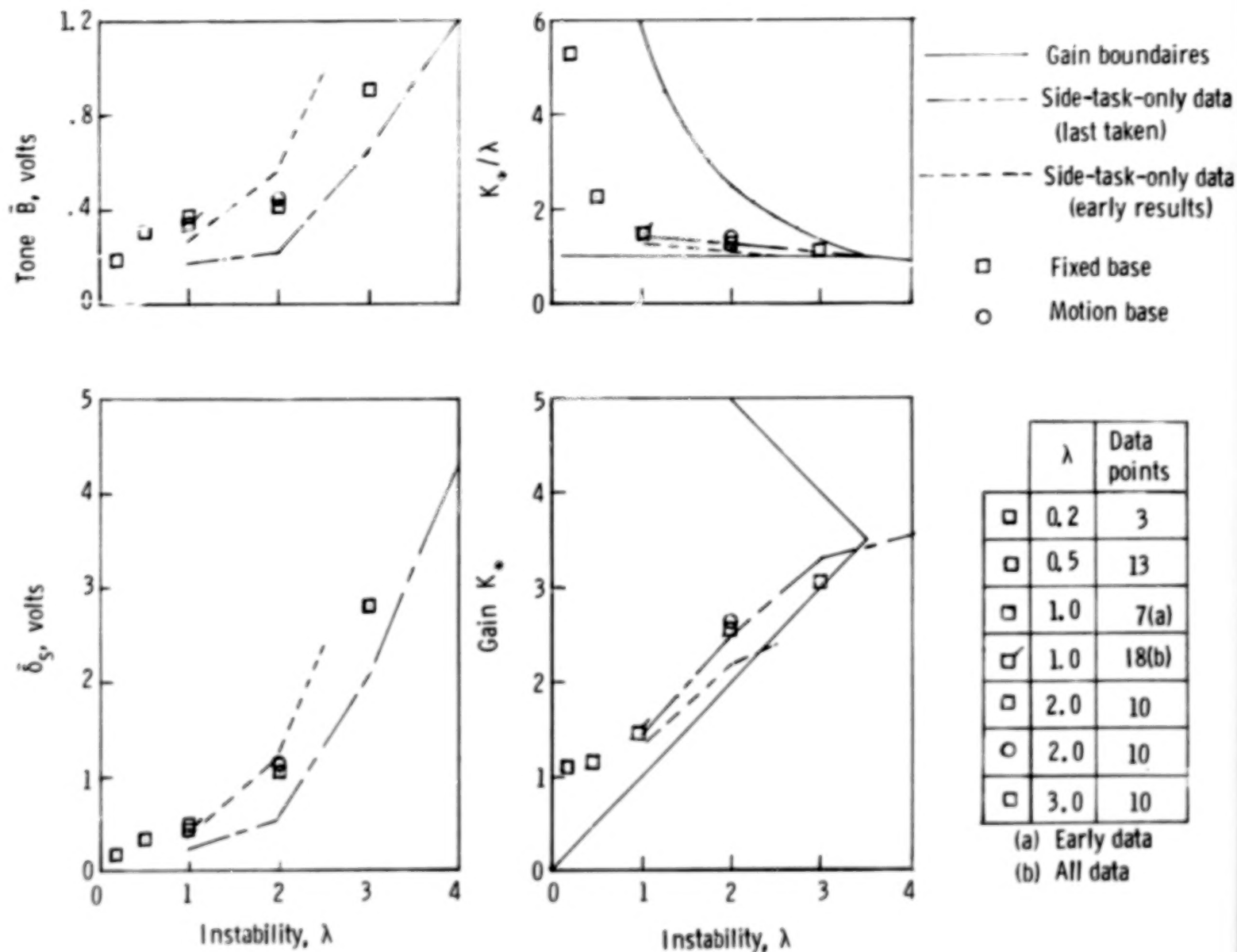
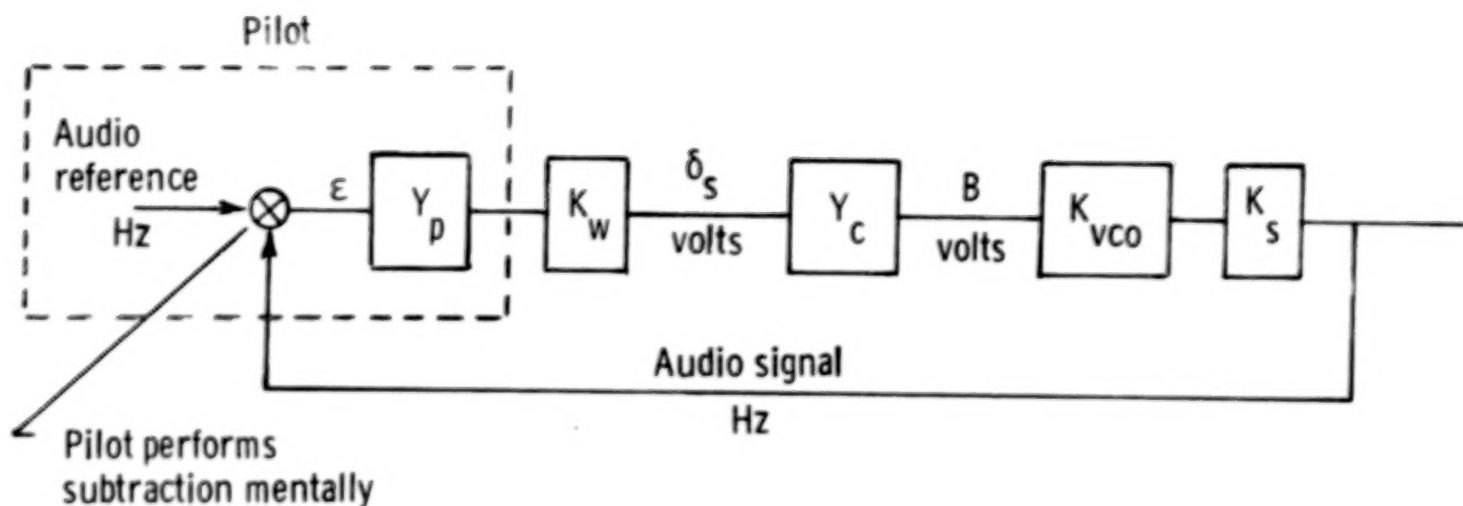


Figure 15.- Comparison of side task data obtained with primary task and with no primary task for subject A.



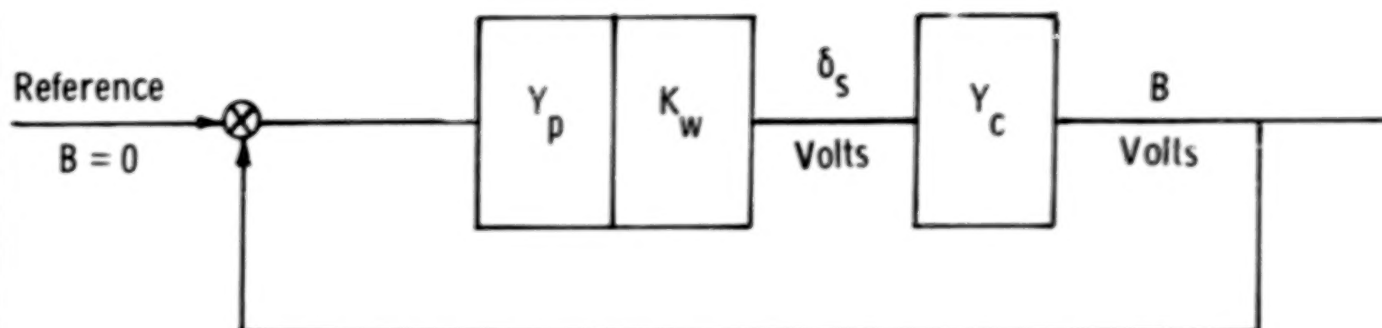
Transfer function

Symbol	Definition	Function
Y_p	Pilot	$K_{pi} e^{-\tau_e s}$
Y_c	Controlled element	$\frac{1}{s - \lambda}$

Gain elements

Symbol	Definition	Output / Input
K_{pi}	Pilot	Wheel rotation, deg / audio signal, Hz
K_w	Thumb-wheel	Volt / wheel rotation, deg
K_{vco}	Voltage controlled oscillator, VCO	
K_s	Speakers	
$K_{vco} K_s$		Audio signal, Hz / volt

Figure 16.- Complete block diagram for audio task with pilot in loop.



Transfer function

Symbol	Definition	Function
Y_p	Pilot	$K_p e^{-\tau_e s}$
Y_c	Controlled element	$\frac{1}{s - \lambda}$

Gain elements

Symbol	Definition	Output / Input
K_p	Pilot gain	Wheel rotation, deg/volt
K_w	Thumb-wheel gain	Volt/wheel rotation, deg

$$K_* = K_p K_w$$

Figure 17.- A simplified block diagram for audio task analysis.

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16 Abstract <p>An experimental study has been made to determine the effect of time delay in the visual and motion cues in a flight simulator on pilot performance in tracking a target aircraft that was oscillating sinusoidally in altitude only. An audio side task was used to assure the subject was fully occupied at all times. The results of the study indicate that, within the test grid employed, about the same acceptable time delay (250 msec) was obtained for a single aircraft (fighter type) by each of two subjects for both fixed-base and motion-base conditions. Acceptable time delay is defined as the largest amount of delay that can be inserted simultaneously into the visual and motion cues before performance degradation occurs. A statistical analysis of the data was made to establish this value of time delay. Use of the audio side task provided quantitative data that documented the subject's work level.</p>			
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